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QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1962

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QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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Oceanography of Saanich Inlet in Vancouver Island, British Columbia[1]

By R. H. Herlinveaux

Fisheries Research Board of Canada
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ABSTRACT

Saanich Inlet is a fjord (24 km long) having a submerged (75-m) sill at the entrance, behind which there is a deep (234-m) basin. The properties of the water have been observed from time to time from 1927 through 1960. The resulting data are reviewed to provide representative values and structures of temperature, salinity, density (σ_t), dissolved oxygen content and sound velocity for each month throughout the year. Above the sill depth the properties of the water are normal and continuous with those in the approaches which connect with the Strait of Georgia. The waters below the sill depth are isolated, oxygen-deficient, and usually contain hydrogen sulphide. There is considerable ambient variation in the structures because the currents are too weak to disperse or mix the locally generated concentrations.

The runoff into the head of the inlet is negligible. The major source of fresh water is in the approaches. It intrudes the inlet and provides a weak estuarine flushing mechanism above the sill depth. The waters below the sill are flushed only when the water in the approaches becomes sufficiently dense to cascade over the sill into the deep basin.

The sound-ranging conditions are far from ideal. From March through July there is a major sound channel at mid-depths above the sill. This vanishes in August and a sound divergence zone develops and persists until December. In addition, the ambient variations provide anomalous transmission conditions.

During the autumn (September through November) high concentrations of fish have been observed at the sill depth, associated with the oxycline. Probably the fish are attracted to the area by very large concentrations of zooplankton (Euphausids) that have been observed there at the same time.

INTRODUCTION

SAANICH INLET, on the southeast coast of Vancouver Island (Fig. 1), has been used in recent years as a testing range for underwater sound-detection gear. During the exercises there have been a number of anomalous occurrences which suggest that the sound velocity structure was variable in distance, depth and time. Since this structure depends on the temperature and salinity structure it is implied that these are variable. Also there was evidence of unusually large concentrations of fish of weight 2 to 4 lb (1 to 2 kg) each, which acted as physical obstacles and provided spurious echoes to sound-ranging gear.

To relieve a somewhat urgent problem, this report constitutes a tentative appraisal of such oceanographic information as has become available over a period of 30 years, amplified to some extent by certain special investigations. In general, it would appear that the lower structure displays reasonable constancy with time. The upper structure, however, varies markedly; and in this context the ensuing discussion is speculative in character, and appreciably contingent on the behaviour of analogous inlets of the British Columbia coast.

To assess the situation, the existing oceanographic information has been studied, and where necessary, special investigations were made. This report reviews the oceanography and the occurrence of fish, and provides adequate reasons for the anomalous sound-ranging conditions.

GENERAL DESCRIPTION

GEOGRAPHY

The inlet, a fjord-like embayment, is situated near the southern end of Vancouver Island (Fig. 1). It includes Saanich Inlet, Squally Reach and Finlayson Arm (Fig. 2). Strictly speaking, the term "Saanich Inlet" applies only to the outer reach. However, in this discussion the term is used to designate the whole embayment.

The inlet is 13 nautical miles (24 km) long[2]. The longest reach (Saanich Inlet) is 10 miles (18.5 km) long and is indented by five major bays. The widest part is from Patricia Bay to Mill Bay (3.9 miles, 7.2 km). There is a sill at the mouth, between Moses Point and Hatch Point, where the limiting depth is approximately 41 fm (75 m). Inward of this sill, the basin deepens to about

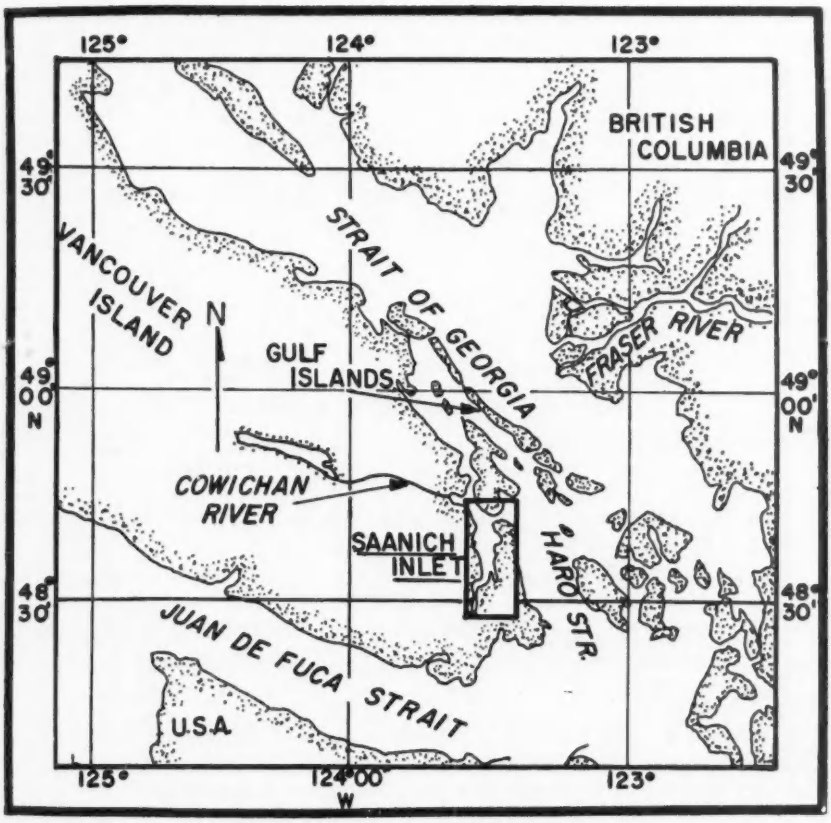

FIG. 1. Saanich Inlet and neighbouring regions.

[2]In the reference chart (Canadian Hydrographic Chart 3451) the depths are shown in fathoms (fm) or feet and distances in nautical miles. Hence these units are used here.

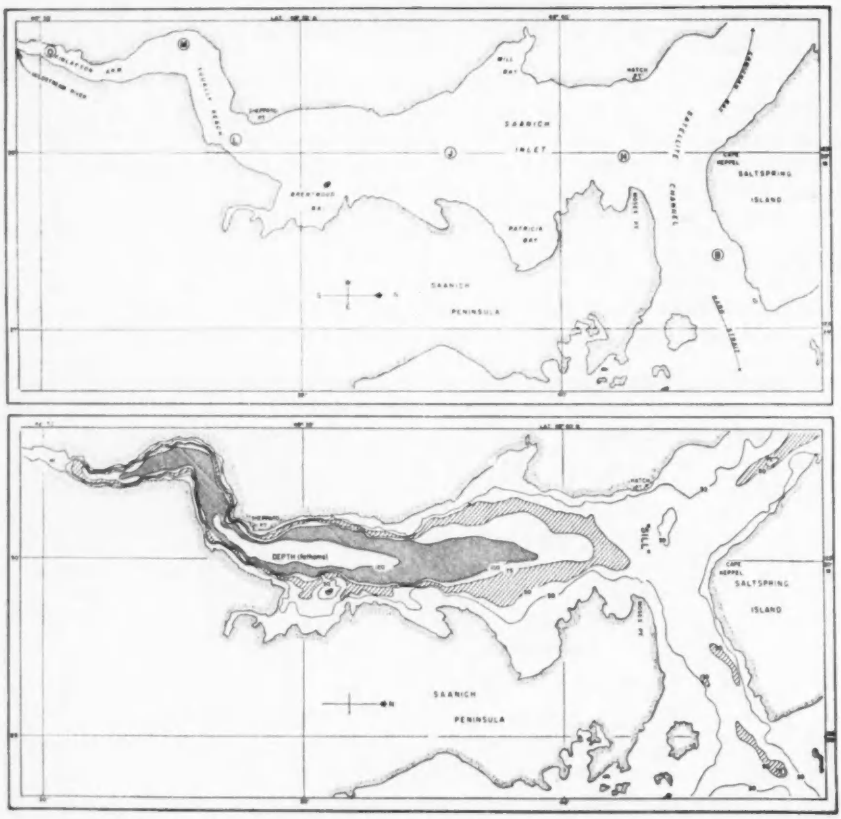

FIG. 2. Oceanographic stations and depth contours in Saanich Inlet.

128 fm (234 m) between Brentwood Bay and Sheppard Point. From there the bottom shoals toward a delta at the head of the inlet.

Clapp (1913) described the geology of the region. Bottom sediments in the inlet consist mainly of sand and mud. The bottom in the deepest part of the basin consists of odious-smelling ooze. This is saturated with hydrogen sulphide, which also has been observed in water samples taken near the bottom.

CLIMATE

A climatic summary of this area was made by Kendrew and Kerr (1955). At Patricia Bay the average annual precipitation is 32.1 inches (81.5 cm). The maximum monthly precipitation occurs in December (5.4 inches, 13.7 cm) and the minimum in July (0.7 inch, 1.8 cm).

The winds are usually seasonal, blowing outward (from the southeast) in summer, and inward (from the west) in winter. Calm periods occur most frequently in summer (July through September).

The air temperatures follow the normal annual cycle similar to that shown by Tully and Dodimead (1957) for Entrance Island in the Strait of Georgia, about 36 miles (67 km) northward of this inlet. The air is coldest in January, and warmest in July.

Runoff

The largest stream, the Goldstream River, enters the inlet at the head. However, the discharge of the river is small (about 30 ft^3/sec, 0.85 m^3/sec). Numerous reservoirs, operated by the Greater Victoria Water District, control most of the runoff resulting from normal precipitation.

Most of the fresh water runoff in the vicinity of the inlet comes from the Cowichan River, which flows into Cowichan Bay (Fig. 1) situated about 3 miles (6 km) north of Saanich Inlet. This fresh water frequently intrudes into the inlet.

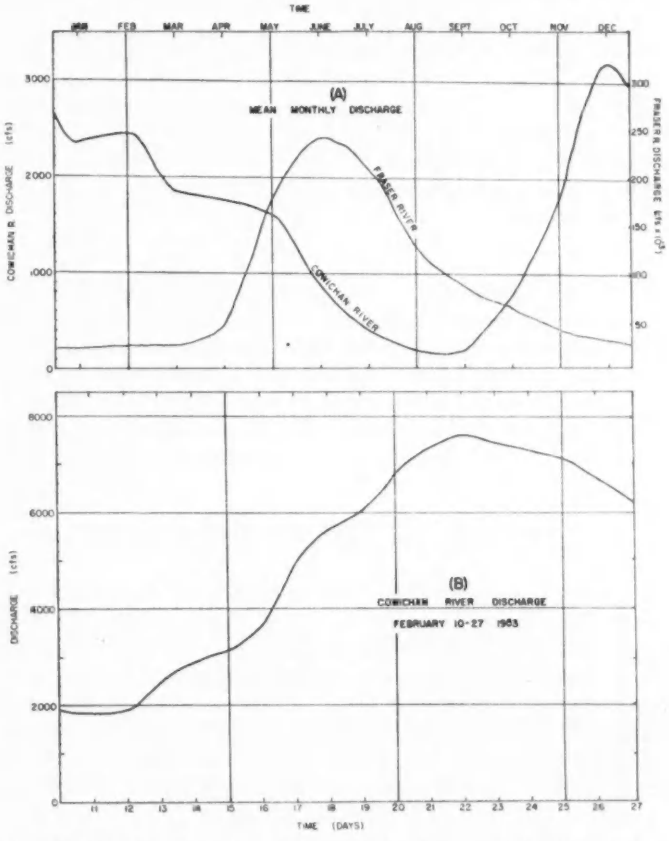

Fig. 3. (A). Mean monthly discharge of the Fraser and Cowichan Rivers. (B). Discharge of the Cowichan River, February 10–27, 1953.

In most other British Columbia inlets which have been studied (Alberni Inlet, by Tully, 1949; Bute Inlet, by Tabata and Pickard, 1957; various inlets, including Saanich Inlet, by Pickard, 1961) the major runoff enters at the head, and develops a two-layer flushing system. By comparison, the fresh water runoff at the head of Saanich Inlet is negligible, and the dominant fresh water influence originates in the approaches. Hence, Saanich Inlet is unique in this respect.

The discharge of the Cowichan River (Fig. 3(A)) (Water Resources Papers, 1941–1953) is representative of the runoff in this area, and closely follows the seasonal precipitation. The discharge is large throughout the winter (December through April) with a maximum usually in December. The minimum discharge occurs in August. Large variations can and do occur in short periods. As shown in Fig. 3(B), the discharge may be doubled in a few days, and tripled in a week. Consequently, large variations in surface salinities in the entrance of Saanich Inlet are observed from week to week.

Also, this region is influenced by the discharge of the Fraser River which is at a maximum in June (Fig. 3(A)). As has been shown by Waldichuck (1957) this discharge creates a brackish upper zone which moves persistently seaward through the Gulf Islands (Fig. 1). Satellite Channel (Fig. 2) in the approaches to Saanich Inlet is part of this system. The intrusion of this low-salinity water from the Strait of Georgia has been confirmed by observations of the characteristic silt-loaded "white water".

Tides

Complete tidal information is given in the Pacific Coast Tide and Current Tables (Canadian Hydrographic Service, Annual). The tides are semi-diurnal and markedly declinational. They are intermediate in range and time between the tides in Juan de Fuca Strait (Victoria) and in the Strait of Georgia (Point Atkinson). The appropriate reference port for Saanich Inlet is Fulford Harbour. The mean tidal range is 8.0 feet (2.44 m) and the maximum is 12.5 feet (3.8 m). Mean sea level is at 8.0 feet (2.44 m) above low water datum.

PROPERTIES AND STRUCTURE OF THE WATER

Data

Oceanographic data in the inlet were first obtained during the summers of 1927 through 1929 (Hutchinson, *et al.*, 1929, 1931). During 1930 and 1931 monthly observations of the properties of the water were made by Carter (1932, 1934). These included temperature, salinity, dissolved oxygen, phosphates, silicates and nitrates, at standard depths. Between 1950 and 1952 several series of observations of temperature, salinity and dissolved oxygen were made. These data have not been reported, but are available in the files of the Pacific Oceanographic Group of the Fisheries Research Board, at Nanaimo, B.C. The Institute of Oceanography of the University of British Columbia (1955 a, b; Pickard, 1961) made comprehensive observations throughout the inlet during May and late August of the years 1953, 1954 and 1955. In 1959 the Pacific Oceanographic

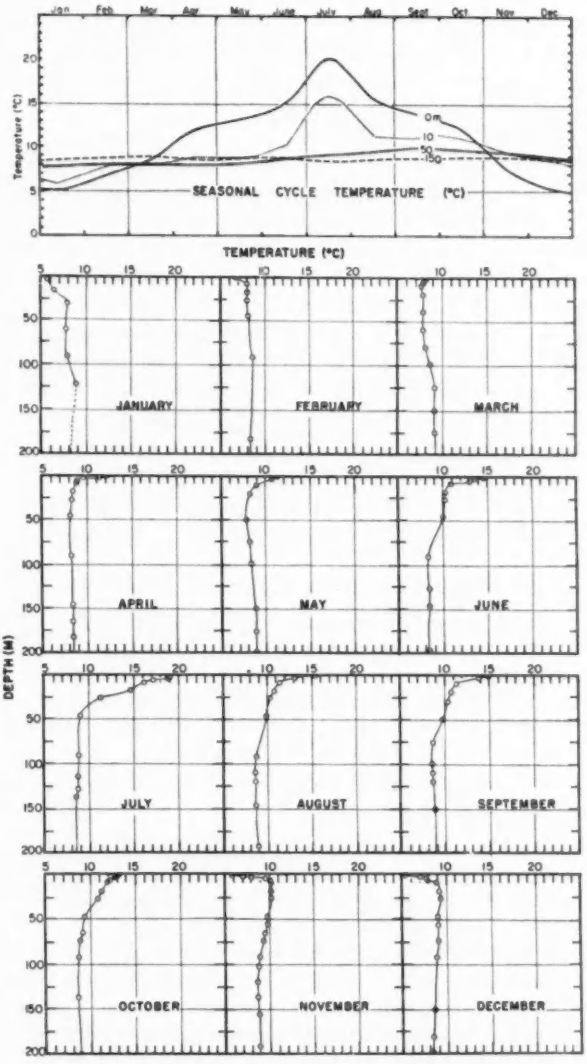

FIG. 4. Seasonal cycle of temperature at selected depths, and the corresponding mean monthly structures at Sta. J in Saanich Inlet, from mean values of data, 1931 to 1960.

Group included the inlet in a program of monitoring the coastal seaways (Pacific Oceanographic Group, MS, 1959a, 1959b; Herlinveaux *et al.*, 1960).

In all this material there is no complete sequence of data through any one year. However, by combining the various data it is possible to describe the distribution and structure of properties that may be expected in each month.

Temperature

Figure 4 shows the mean monthly temperatures at four depths, and the corresponding structures at Station J (Fig. 2) assembled from all usable data collected from 1930 to 1959. The amounts of data are not the same in each month, however there are sufficient data for reasonable presentations.

The diagrams show that there is an annual cycle of temperature in the near surface waters, with a marked maximum in July. At greater depths (50 m) the cycle becomes less evident, and the maximum occurs later in the year. This is similar to the temperature cycle in the Strait of Georgia (Tully and Dodimead, 1957). At 150 m the temperature is nearly constant throughout the year. In the winter, November through February, the surface waters are colder than the deep waters, hence a positive gradient (temperature increasing with depth) prevails. Surface warming commences in March, creating near the surface negative temperature gradients which reach a maximum in July. Below this, the temperature minimum persists. The negative temperature gradients diminish and vanish in November.

Figure 5 shows observed structures in longitudinal sections at four times of the year. In each instance there are minima or maxima in the structure. In March there was a relatively cool (less than 7.8°C) sub-surface layer in the outer part of the inlet. In June the minimum was warmer (8.5 to 9.0°C) but was present at intermediate depths throughout most of the inlet. The August data are not in sequence with the other data presented here. However, the dissipation of the minimum at this time is representative of late summer conditions. In November there was a sub-surface temperature maximum (10.0°C) at 35 m throughout most of the inlet.

The sequence of structures shows that the temperature minima and maxima were not evident in the approaches (Satellite Channel). They were shallowest immediately inward of the sill, then deepened and became thicker toward the head of the inlet.

Figure 6 shows both the surface distribution of temperature and a sequence of structures observed along the inlet in June 1959. These correspond to the June data of Fig. 5. The warmest surface water occurred in the middle of the inlet (between Sta. L and J), and there were small horizontal gradients at the head and mouth. Other surface plots (not shown) indicate that there were similar gradients in other seasons although the temperature levels were different as indicated in Fig. 4 and 5.

It is notable that the thermocline intercepts the surface along the entire inlet. This feature is evident in all the data (Fig. 4 and 6). In the nearby Strait of Georgia, Waldichuck (1957) and Tully and Dodimead (1957) observed

an isothermal layer about 5 m deep, overlying the thermocline. They attributed this isothermal layer to wind mixing. Evidently the wind in this inlet and approaches is not sufficient to mix the surface waters.

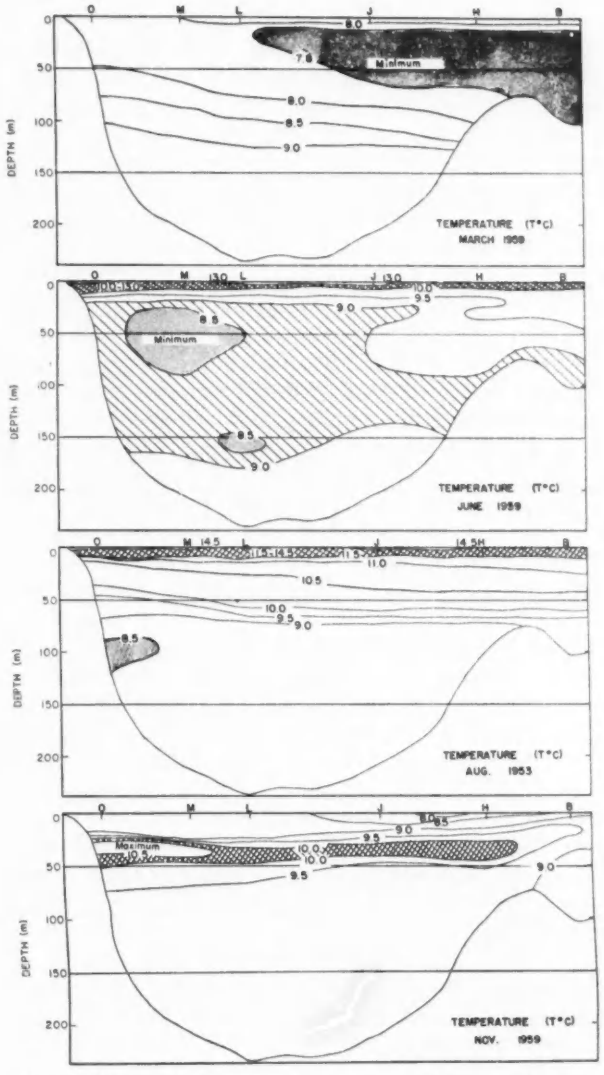

FIG. 5. Observed temperature structures in a longitudinal section of Saanich Inlet.

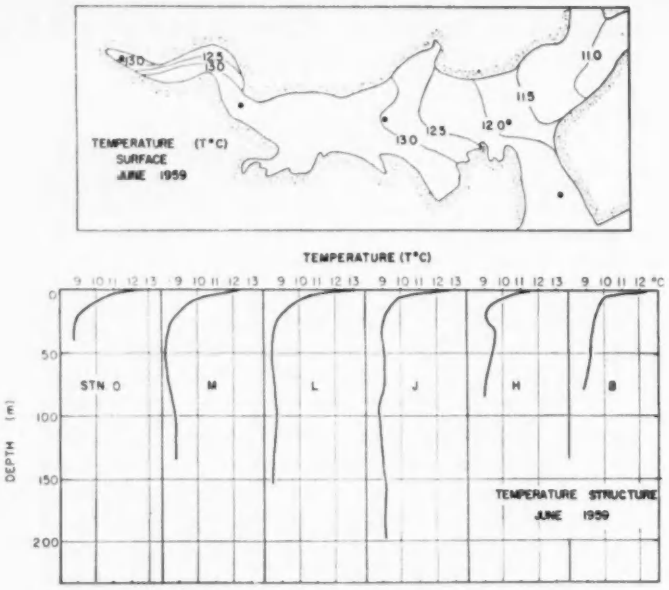

FIG. 6. Observed surface temperature and structures in Saanich Inlet, June 1959.

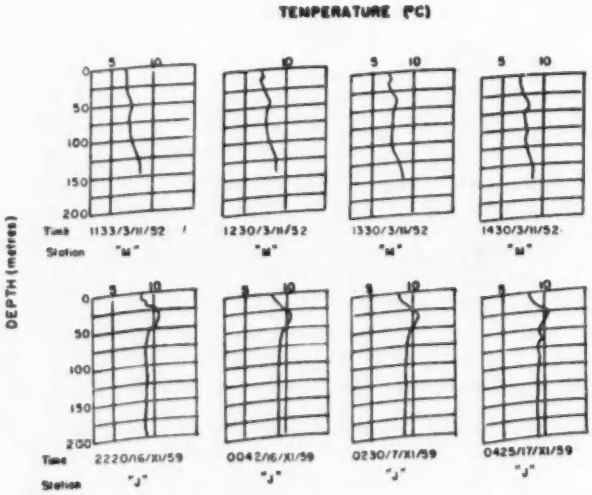

FIG. 7. Samples from series of bathythermograms observed in Saanich Inlet.

Tabata and Pickard (1957) have described the mechanics of the seasonal sequence of temperature structures in Bute Inlet, which are similar to those in Saanich Inlet. In winter, in both inlets, the surface waters become colder than the deep waters (Fig. 4). They are density stable because the positive salinity gradients persists. In March the winter-cooled waters reach their greatest depth, about 100 m. Thereafter, as the surface waters are warmed through spring and summer, the remnants of the winter-cooled waters persist below the thermocline, and may be identified by the temperature minimum. These cooler waters are gradually dissipated by flushing, entrainment, or mixing with the surrounding waters. This process is nearly complete by the end of August. Thereafter, the surface waters are cooled and a temperature maximum at depths becomes evident during winter. This is the remnant of the summer thermocline which deepens and dissipates through the winter, in much the same manner as the temperature minimum. Convective overturn is not a feature of this process, since, as will be shown, the positive salinity gradients persist in this zone of heating and cooling, and maintain the stability throughout the year.

In Fig. 5 and 6, there are evidences of isolated volumes of water which are slightly warmer or cooler than their surroundings. Figure 7 shows samples from two series of bathythermograms observed at hourly and 2-hourly intervals. These show that there were significant variations in the structure in periods of 2 hours or less in February (II) and November (XI). Similar data are summarized in Fig. 8 as the sequence of temperatures at several levels. Table I shows the limits of the values at several depths, observed during six time-series observations at Sta. J. Considering all these data (Fig. 5, 6, 7, 8 and Table I), it is evident that short-term variations occur in the structure at all times of the year. These are greatest in the near-surface waters, and are least, but still apparent, in the depths.

Part of the variation appears to occur in a tidal period, and may be consequent on the tidal excursion in the presence of a longitudinal gradient (Fig. 6) or to some sort of tidally induced internal wave system. From time to time there are marked changes, or irregular values. These may be visualized as occluded masses of relatively warm or cool water, superimposed on the dominant structure. Such variations have been observed to the same or greater degree in Juan de Fuca Strait (Herlinveaux and Tully, 1961) and along the ocean coast of Vancouver Island (Lane, 1962).

Corresponding variations were observed in the other properties in Saanich Inlet.

Salinity

Figure 9 shows the mean monthly salinities at four depths, and the corresponding structures at Sta. J, assembled from all usable data collected from 1930 to 1959. These correspond to the temperature data shown in Fig. 4.

There is a positive salinity gradient at all times, though most marked near the surface. Winter dilution is apparent in the surface waters (0 to 10 m depth) but not at 50 m depth. It coincides with the winter precipitation and with the

TABLE I. Observed maxima and minima of temperature, salinity, dissolved oxygen and sound velocity at Station J.

Depth (metres)	24 hours Feb. 1952		7 hours May 1954		26 hours May 1955		30 hours June 1959		12 hours Aug. 1953		32 hours Nov. 1959	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Temperature, °C:												
0	6.89	5.06	13.90	12.00	11.64	10.12	13.10	12.50	13.96	13.05	8.50	7.60
10	7.39	6.78	9.60	9.42	8.87	8.36	9.90	9.60	11.57	10.84	8.96	8.30
50	8.22	7.61	8.05	7.85	8.01	7.41	9.30	9.00	9.80	9.58	9.43	9.04
150	8.33	7.89	–	–	8.77	8.60	9.12	9.09	8.76	8.72	9.17	9.12
Salinity, S‰:												
0	29.14	19.10	28.95	28.70	28.48	25.03	29.00	28.70	29.30	29.17	28.62	28.37
10	30.16	29.83	29.31	29.20	29.59	29.47	29.30	29.20	29.60	29.52	28.78	28.56
50	30.68	30.10	29.98	29.78	30.01	29.90	30.20	30.00	30.23	30.02	30.15	29.90
150	31.40	31.20	31.26	31.08	31.27	31.18	31.21	31.19	31.24	31.15	31.22	31.18
Dissolved oxygen, ml O_2/l:												
0	–	–	13.36	12.49	11.73	10.42	14.01	11.99	9.69	7.98	9.10	7.77
10	–	–	15.08	11.68	10.49	9.38	8.83	7.09	5.62	5.05	8.35	6.90
50	–	–	7.38	7.16	8.08	7.39	7.08	6.65	4.17	3.94	6.45	4.62
150	–	–	0.26	0.08	0.31	0.19	0.13	0	0.15	0	0.24	0
Sound velocity, ft/sec:												
0	4818	4773	4910	4888	4882	4864	4899	4894	4912	4879	4845	4832
10	4833	4826	4862	4860	4853	4847	4865	4862	4887	4878	4852	4843
50	4851	4847	4847	4846	4847	4838	4864	4860	4870	4864	4865	4857
150	4869	4862	–	–	4868	4866	4872	4871	4867	4866	4873	4872

runoff of the nearby Cowichan River (Fig. 3). The summer dilution coincides with the maximum runoff of the Fraser River, and is evident to about 50 m depth.

These conclusions are confirmed by the data of Fig. 10, which were observed in the several seasons. The isohalines above the sill depth are continuous with those in the approaches. However, the deep waters appear to be isolated.

Figure 11 shows two types of surface salinity distribution and the corresponding structures observed in the inlet. The data of May 1955 were observed

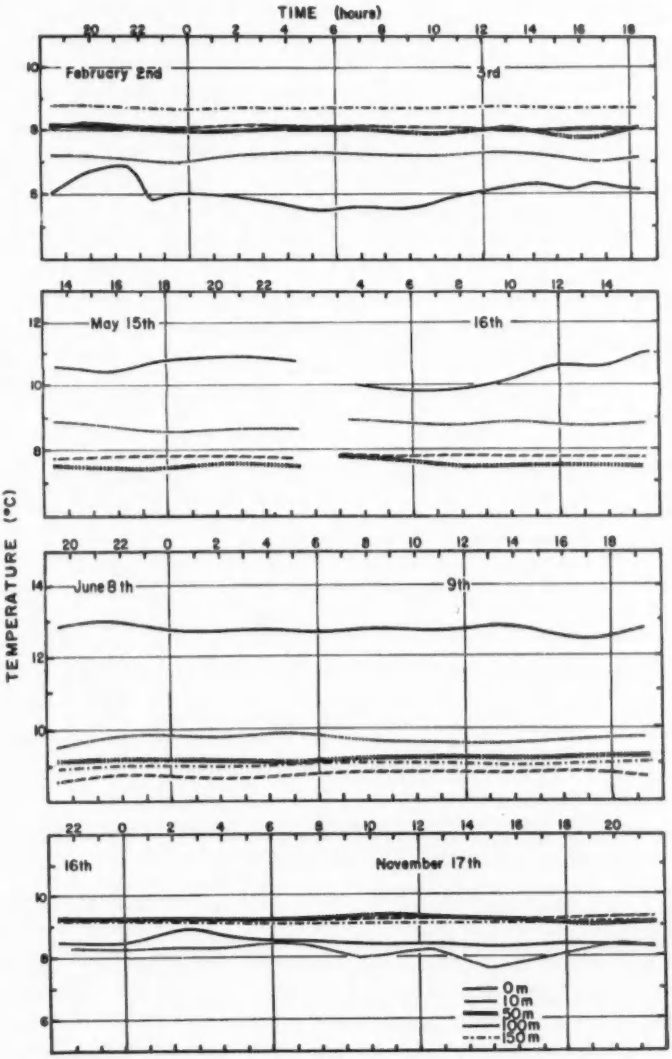

FIG. 8. Observed temperatures at selected depths in Saanich Inlet at four times of year.

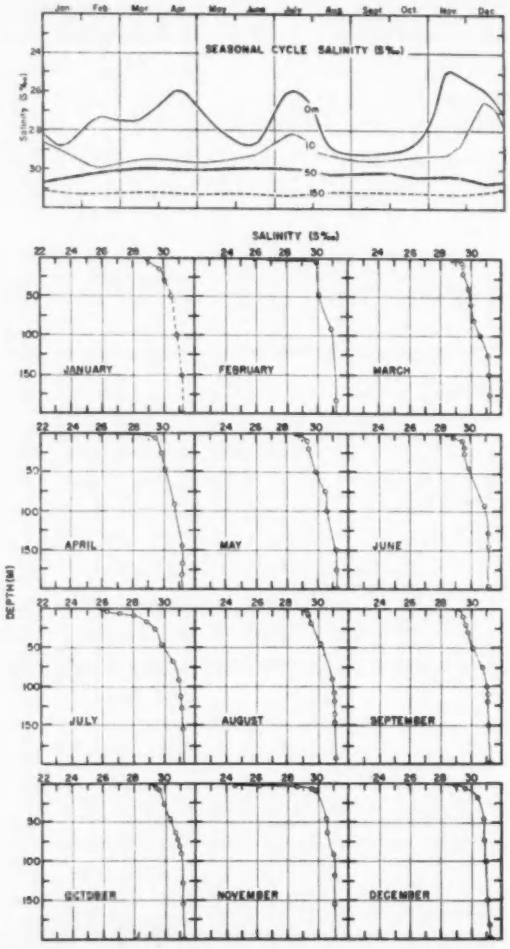

FIG. 9. Seasonal cycle of salinity at selected depths and the corresponding mean monthly structures at Sta. J in Saanich Inlet, from mean values of data, 1931 to 1960.

following a period of average runoff from the Cowichan River (1400–1500 ft^3/sec). The lowest salinities define the region of fresh water influence, which extends into the inlet along the western side. Between the mouth and the head, the distribution of salinity was irregular (cloud-like). In June 1959 the observations were made after a period of small runoff from the Cowichan River (600–800 ft^3/sec). In these observations there was very little evidence of fresh water intrusion, and the surface salinities were nearly constant over the inlet. The structures show that the direct fresh water influence was limited to the upper 10 m.

The brackish water near the entrance to the inlet occurs in isolated "clouds". These are consequent on the intermittent discharge from the Cowichan River and Cowichan Bay, which is regulated by the tide. The presence of such clouds in the vicinity of the Fraser River has been explained by Tully and Dodimead (1957). Fresh water is discharged during the falling tide. The outflow is retarded or reversed by the rising tide. Such intermittent outflow isolates clouds of brackish water at the surface.

It is notable in these structures that there was no isohaline upper zone, such as occurs in the Strait of Georgia (Waldichuk, 1957; Tully and Dodimead, 1957). Rather, the halocline extends to the surface at all times of the year (Fig. 9). This situation corresponds to the lack of a mixed layer in the temperature structure, and indicates a lack of wind mixing in the inlet.

In the salinity structures (Fig. 11) there are usually two haloclines, one near the surface, and one at the sill depth (75 m). These features are also apparent in the average data (Fig. 9). According to the concepts discussed by Tully (1958) this feature would suggest that the waters above the deep halocline belong to a regime different from those below it. This conclusion will be confirmed in the discussion of mechanism.

There is no evidence of cloud structure in the illustrated sub-surface salinity structures (Fig. 9, 10, 11) because the salinities were observed at discrete depths. However, as shown in Table I, there are variations of salinity at the selected levels, which are largest at the surface, and small in the depths.

Temperature–Salinity Relations

Figure 12 shows representative temperature–salinity relations compiled from all available data (1930–1959). These form a fan with one limit in September and the other in January. The curves representing conditions in June through October form a distinct group in which the temperature is the dominant variable. Another group is formed by the data of December through March in which the salinity is dominant. The transitional curves are those for April and November. The curves are long in July because of surface heating, and in November because of the dilution of the surface waters by large runoff. The shortest curve occurs in March when there is no surface heating and the runoff is small.

Density[3] (σ_t)

Figure 13 shows the mean monthly densities (σ_t) at four depths, and the corresponding structures assembled from all usable data (1930–1959). The surface densities are variable, corresponding to the temperatures (Fig. 4) and the salinities (Fig. 9). In the sub-surface waters, below 10 m depth, the low densities occur only in mid-summer, and are associated with the seasonal intrusion of Fraser River water.

As would be expected from the temperature and salinity data, there is no mixed layer. There is a marked surface pycnocline at all times. It is associated with the thermocline in summer and the halocline in winter. Below this there

[3]Density is expressed here as $\sigma_t = (\text{specific gravity} - 1) \times 1000$ (Sverdrup *et al.*, 1942, p. 56).

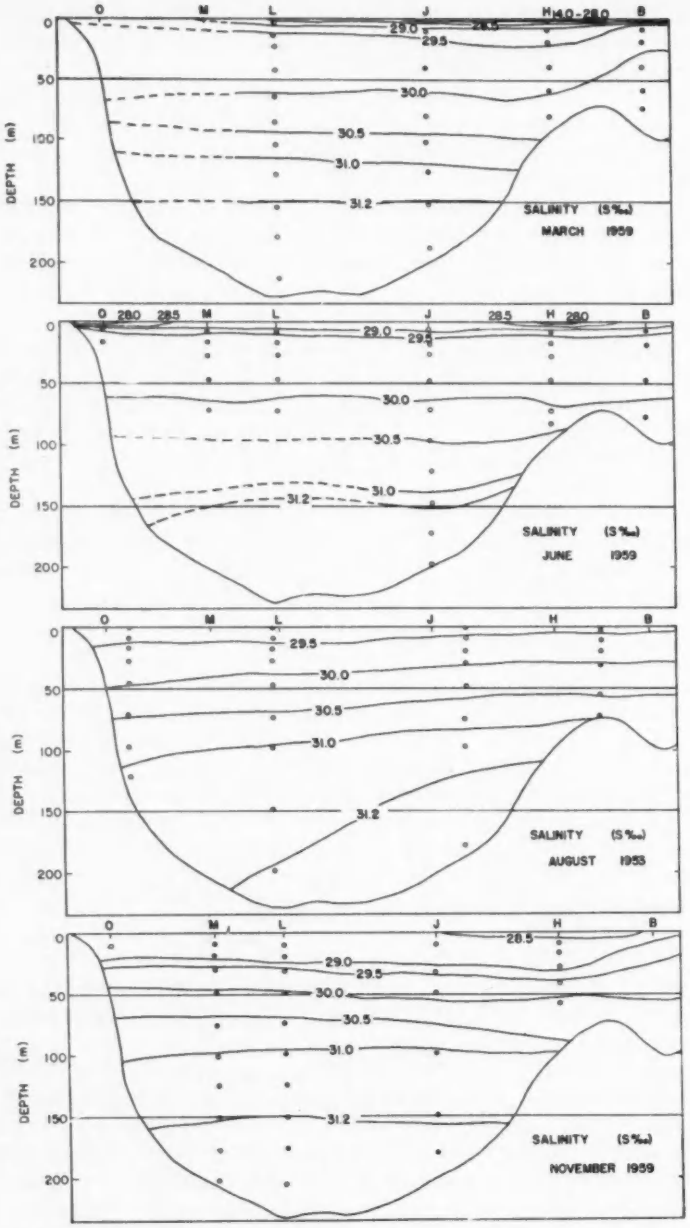

FIG. 10. Observed salinity structures in a longitudinal section of Saanich Inlet.

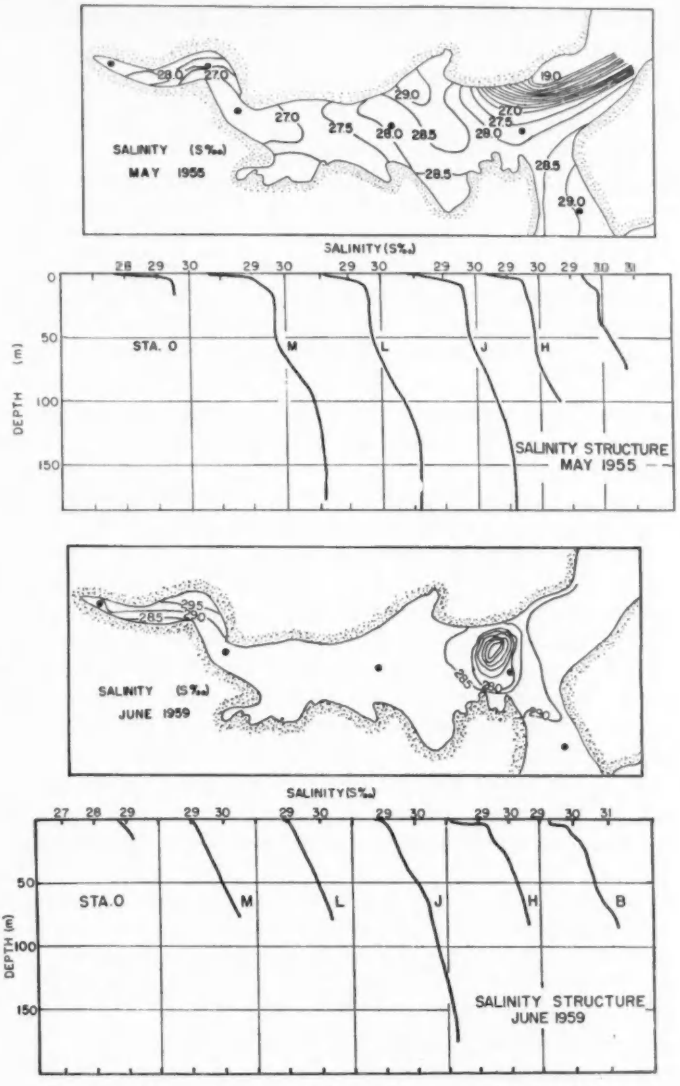

FIG. 11. Observed surface salinities and structures in Saanich Inlet.

is a small density gradient to the sill depth. In the depths the waters are very nearly isopycnal.

These conclusions are confirmed in the longitudinal sections (Fig. 14) constructed from observed data. The isopycnals at sill depth and above appear

to be continuous over the sill. However, the deep waters appear to be isolated from the water in the approaches.

Figure 15 shows the two types of surface density distribution and structures, corresponding to the two types of salinity distribution shown in Fig. 11.

Dissolved Oxygen

Figure 16 shows the mean monthly concentrations of dissolved oxygen at four depths, and the corresponding structures at Sta. J, assembled from all usable data collected from 1930 to 1959. These correspond to the temperature, salinity, and density data shown in Fig. 4, 9, and 13.

In the waters above the sill depth there are broad minima in late winter and autumn. At 150 m depth the values are representative of the waters below the sill depth. Here, there appears to be no dissolved oxygen throughout most of the year.

These conclusions are confirmed in the longitudinal presentations of observed data in Fig. 17, which emphasize the near-surface maximum in the summer, and the zero, or very low, oxygen concentration below the sill depth throughout the year. The iso-oxys above the sill depth appear to be continuous with those in the approaches. The waters below the sill depth are obviously isolated. At all seasons there are one or more oxyclines in the structure.

As shown in the upper diagram of Fig. 18 the concentration of dissolved oxygen at the surface increased from the mouth of Squally Reach in June 1959. The highest concentrations were along the eastern shore. This condition is representative of the summer data. The structures shown in the lower diagram indicate both a high concentration in the upper 10 m and a near-surface maximum. Below this, the oxygen concentation decreased regularly with depth, and vanished in the bottom waters.

These diagrams show that there were two oxyclines in the structure, one associated with the surface, and one with the sill depth. Figure 16 shows that these are generally present, although only one oxycline was present in August 1953 (Fig. 17).

Carter (1934) observed that the deep waters of the inlet were devoid of oxygen on several occasions and that the bottom ooze and deep waters contained hydrogen sulphide. He believed that this condition was permanent. However, later data, such as shown for August 1953, indicate that there can be some replenishment of the dissolved oxygen from time to time.

In these diagrams there is considerably more evidence of isolated clouds of low oxygen concentration than there was for isolated clouds in the corresponding temperature (Fig. 5) or salinity (Fig. 10) structures. These are confirmed by the large limits of variation shown in Table I.

Plankton and Dissolved Oxygen

Hutchinson and Lucas (1931) have recorded the occurrence of large phytoplankton crops during the heating season (April through July). Also, accumulations of dislodged benthic algae at the head of the inlet are frequently visible

from the Malahat Highway along the west side of the inlet. This material forms large "rafts" or visible cloudy patches in the water.

The planktonic and benthic algae are photosynthetic and generate excess oxygen during the long summer days. This is probably the source of the high oxygen concentrations (supersaturation) in the near-surface waters (Fig. 16, 17, 18). When the algae (particularly benthic) die they sink and decay, creating an oxygen demand. This probably creates the zone of oxygen deficiency below

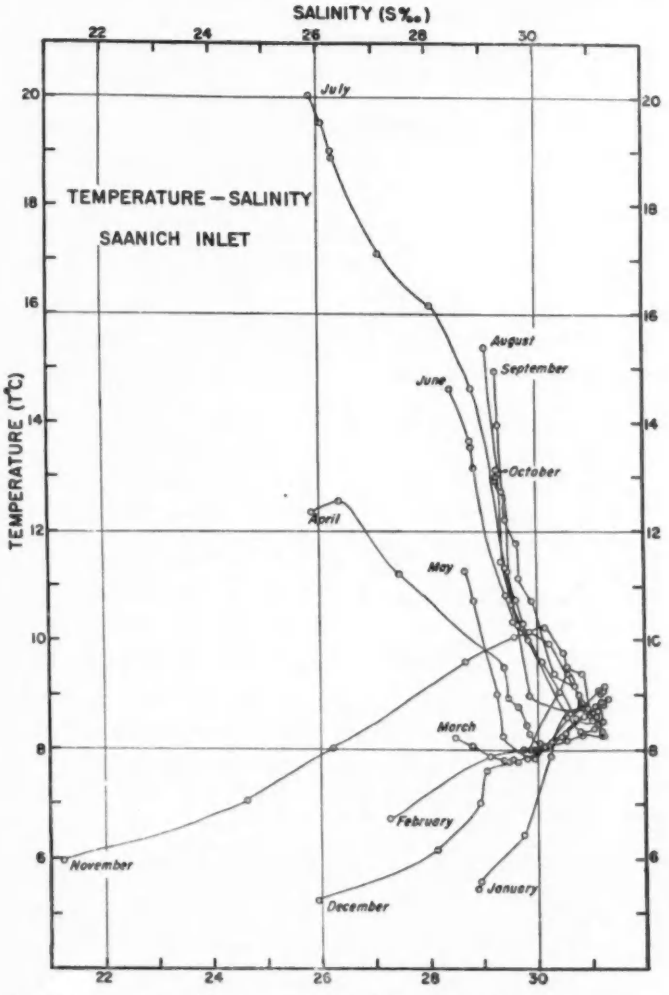

FIG. 12. Mean monthly temperature–salinity relations at Sta. J in Saanich Inlet, from mean values of data, 1931–1960.

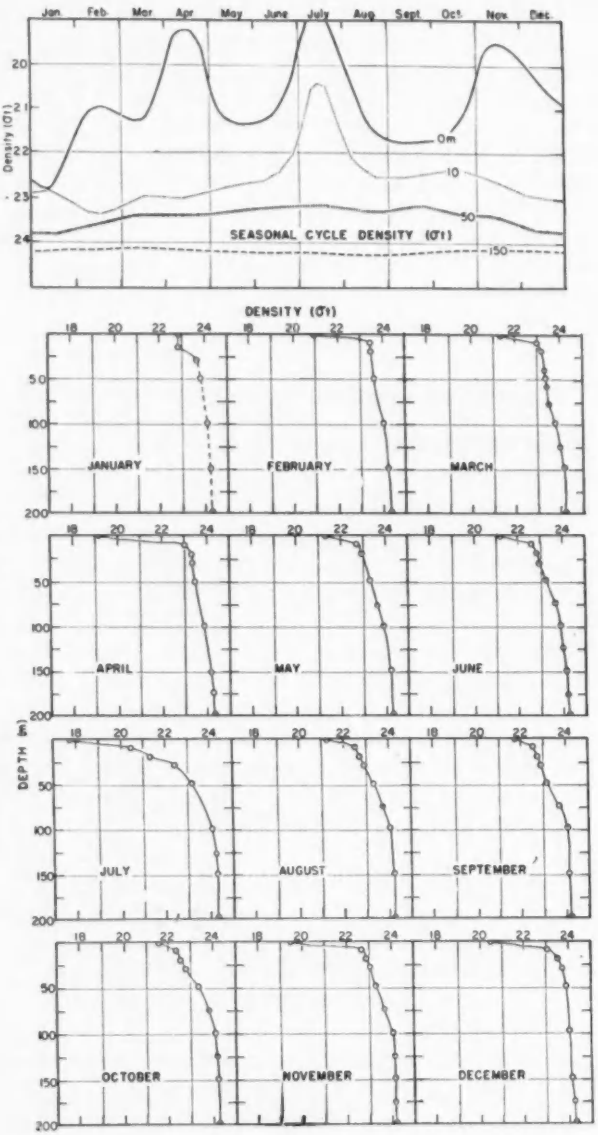

FIG. 13. Seasonal cycle of density (σ_t) at selected depths, and the corresponding mean monthly structures at Sta. J in Saanich Inlet, from mean values of data, 1931–1960.

the surface layers. It is reasoned that the cloud-like distribution of dissolved oxygen in these regions is probably consequent on the cloud-like distribution of the algae, and the lack of a vigorous circulation and mixing.

Below the sill depth the circulation is even weaker, so that the continued demand removes the last traces of dissolved oxygen. In this environment the decay must be anaerobic. Eventually, the excess organic material collects on the bottom as odious ooze, saturated with hydrogen sulphide.

Plankton hauls were made on October 17, 1960 (Lane *et al.*, MS, 1960). These were not adequate to give a complete assessment of the biological features, but did indicate that there was a relatively high concentration of phytoplankton (primarily *Chaetoceros convolutus*) in the upper 10 to 15 m during this period. Further, numerous species of zooplankton were caught in low concentrations at approximately sill depth at Sta. J. At dusk, large numbers of Euphausids were caught at approximately 30 to 40 fm (55 to 73 m).

Turbidity

During the early oceanographic investigations of Saanich Inlet turbidity was often estimated from the limiting depth at which a water sampling bottle was visible, though a Secchi disc or other means were sometimes used. In 1959 turbidity was regularly observed with a Secchi disc (30 cm diameter). These observations indicated that the turbidity was greatest during the summer months (April through July) and least during the winter months. This is similar to the occurrence of high oxygen concentrations. It also coincides with the season of greatest phytoplankton concentrations (Hutchinson *et al.*, 1929).

Turbidity measurements were taken on October 17, 1960 (Lane *et al.*, MS, 1960) from the surface to 88 m with a 1-m horizontal turbidity meter. These data giving extinction coefficients for both red and blue light (Strickland, 1958) are presented in Fig. 19, which shows that the extinction coefficients (turbidity) decreased from the surface to a minimum at 30 to 40 m and increased to surface values at approximately 80 m. The surface-layer maximum coincides with the greatest phytoplankton concentration. The lower turbid layer (80 m) coincides with the top of the oxygen deficient layer and with the bottom of the thermocline, halocline and pycnocline which are also shown in Fig. 19. This suggests that the turbid layer is dependent on the physical structure. The difference between the red and blue extinction coefficients is greatest at 80 m depth, which indicates that this turbid layer contains colloidal particles, probably detritus. Further investigation is required to confirm these deductions.

Sound Velocity

Sound velocity changes about 4 feet per second[4] with a change of 1‰ salinity, about 12.5 ft/sec with a change of 1 C° temperature, and 6 ft/sec with a change of 100 m depth.

Usually the temperature differences are numerically greater than the salinity differences in oceanographic situations, and dominate the sound velocity struc-

[4]The unit feet per second (ft/sec) is used in practically all the literature on sound velocity. Hence it is used here.

ture. In water that is isohaline and isothermal, the sound velocity increases with depth.

Figure 20 shows the mean monthly sound velocities at four depths at Sta. J, and the corresponding structures. These were calculated from all usable temperature (Fig. 4) and salinity (Fig. 9) data collected from 1930 to 1959.

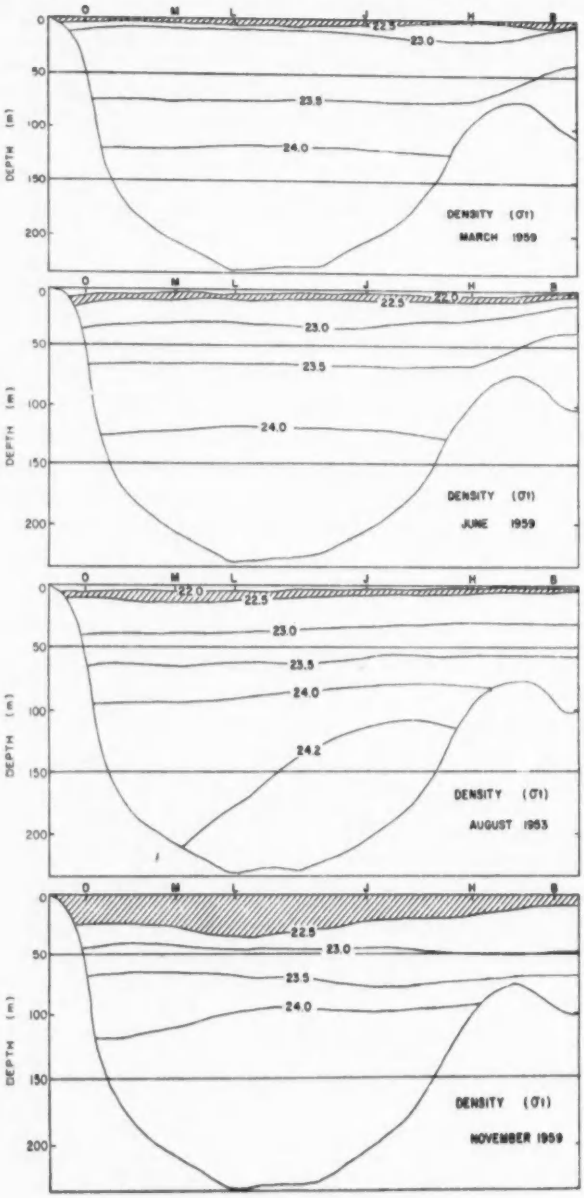

FIG. 14. Observed density (σ_t) structures in a longitudinal section of Saanich Inlet.

Near the surface there is a single annual cycle with a marked maximum in July and a broad minimum in winter. Below 50 m depth, the cycle is not apparent.

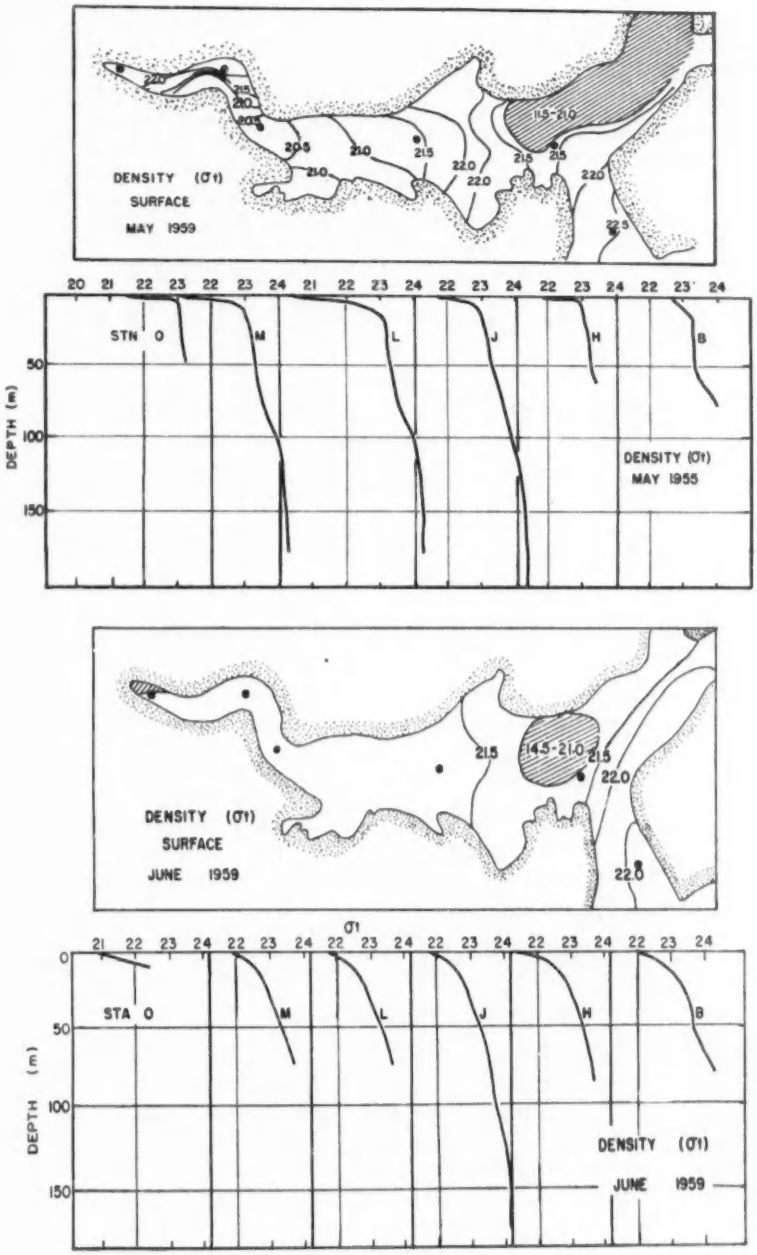

FIG. 15. Observed surface densities (σ_t) and structures in Saanich Inlet.

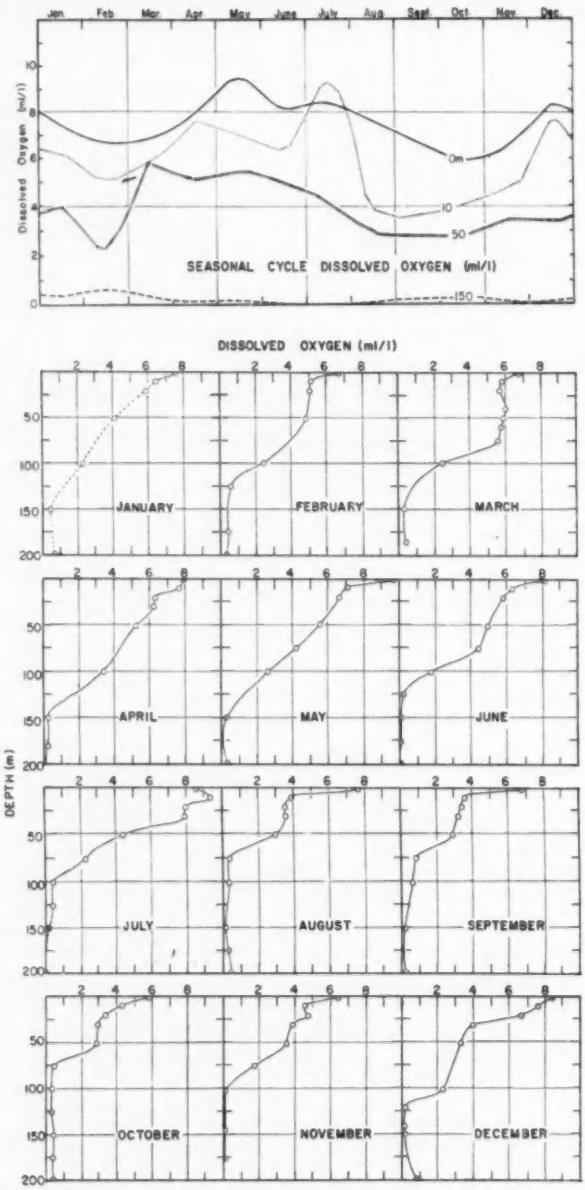

FIG. 16. The seasonal cycle of dissolved oxygen at selected depths, and the corresponding mean monthly structures at Sta. J in Saanich Inlet, from mean values of data, 1931 to 1960.

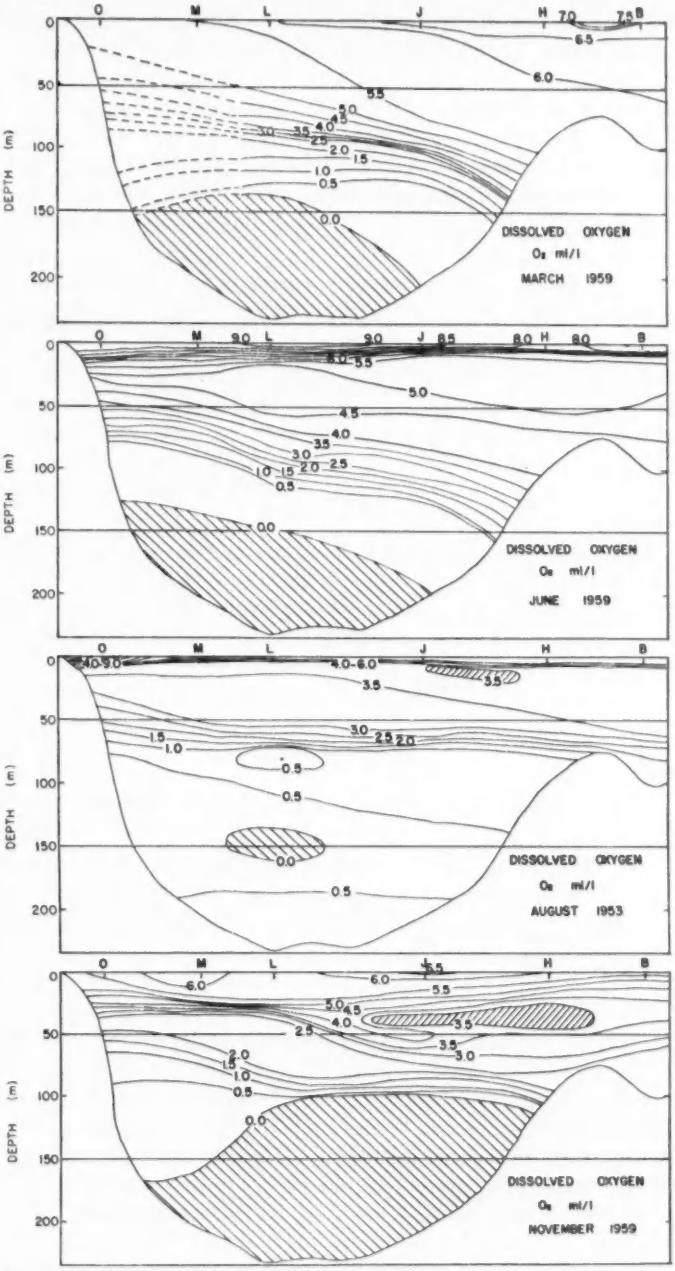

FIG. 17. Observed structures of dissolved oxygen in a longitudinal section of Saanich Inlet.

The features of the annual cycle of sound velocity structure are confirmed in Fig. 21 and may be considered along with the mean monthly structures in Fig. 20. In late winter (March) the vertical gradient is generally positive (increasing with depth). In spring and early summer, as surface warming develops, the sound velocity in the surface layers increases. A sound velocity minimum (duct) is developed at intermediate depths (20 to 80 m) coincident with the temperature minimum (Fig. 5) which was shown to be the remnant of winter-cooled water. This minimum sinks and is dissipated entirely as the summer passes. Then there is a simple negative gradient. In autumn, when surface cooling occurs, a sound velocity maximum (divergence zone) develops, coincident with the temperature maximum (Fig. 7), which was shown to be the remnant of the summer thermocline. During the winter the maximum sinks and is dissipated.

Figure 22 shows that at the surface, there was a gradient of increasing sound velocity from the mouth to Sta. J near Mill Bay. It is believed that the isolated area of low sound velocity (4850 ft/sec) is associated with a cloud of brackish water (Fig. 11) and is a transient feature. The accompanying structures show some inversions.

Table I shows that there are variations of sound velocity which are greatest at the surface and smaller in the depths. It may be concluded that these variations, like the variations of temperature, betray cloud-like irregularities in the sound velocity structure. It is quite possible for velocity inversions of as much as 3 to 4 ft/sec to occur and be stable.

MECHANISMS

Currents

Several attempts were made to measure the currents at Sta. J (Fig. 2) using an Ekman current meter suspended from an anchored ship. The observed currents were close to the limits of error of the instrument (5 cm/sec, 0.1 knot) in all (10 hours) except one observation. Also the recorded directions were erratic. In one measurement the current was 23 cm/sec setting diagonally across the channel to the northwest. From these data it was concluded that the currents were small and variable, and probably had little or no consistent pattern. There are probably occasional local surges.

Doubtless the surface currents are determined by the winds. When the wind blows the surface water to seaward (northward) there will be a deficiency of water at the head of the inlet. This condition will require a compensating, inward subsurface movement. When the wind blows into the inlet, surface water will accumulate towards the head. Then the compensating subsurface flows will be outward. Immediately following a period of strong winds, there will be strong relaxation currents for short periods (a few hours) in the near-surface layers.

Since there is a tidal rise and fall in the inlet there must be tidal currents. During the rising tide, water from the approaches advances into the inlet, com-

pressing the resident water to the extent of the tidal rise. The distribution of the brackish water from Cowichan Bay (Fig. 11) suggests that the greatest intrusion is along the western side. It is probable that the ebb movement is greatest on the eastern side, because the ebb flow is eastward in Satellite Channel. Such tidal movements must diminish towards the head of the inlet. This is partially confirmed in the data which show that the surface properties there are somewhat different from those in the seaward reaches. Evidently these waters are partially isolated, or slowly flushed.

Estuarine Flushing

The fresh water from the Goldstream River at the head of the inlet, and from the Cowichan River in the approaches, does not accumulate in the inlet. The effects of the Fraser River freshet become evident in season, and do not persist. Hence it may be concluded that there is effective exchange of near-surface waters with the nearby seaways. It is probable that the principal exchange occurs through Satellite Channel to Haro Strait, since this is the shortest, widest and deepest route.

It has been shown (Tully, 1958) that light (fresh) water entering an embayment moves persistently seaward over the surface. En route it entrains sea water from below to form a brackish upper zone, in which the density (salinity) increases to seaward. Hence, when the near-surface waters in the inlet and vicinity are less dense than the near-surface waters in Haro Strait, there must be a persistent surface movement toward Haro Strait, superimposed on the reversing tidal movement.

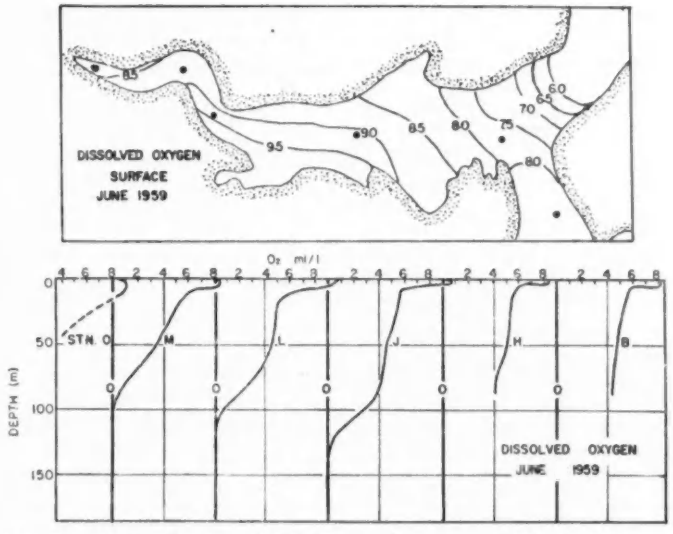

FIG. 18. Observed surface distributions and structures of dissolved oxygen in Saanich Inlet.

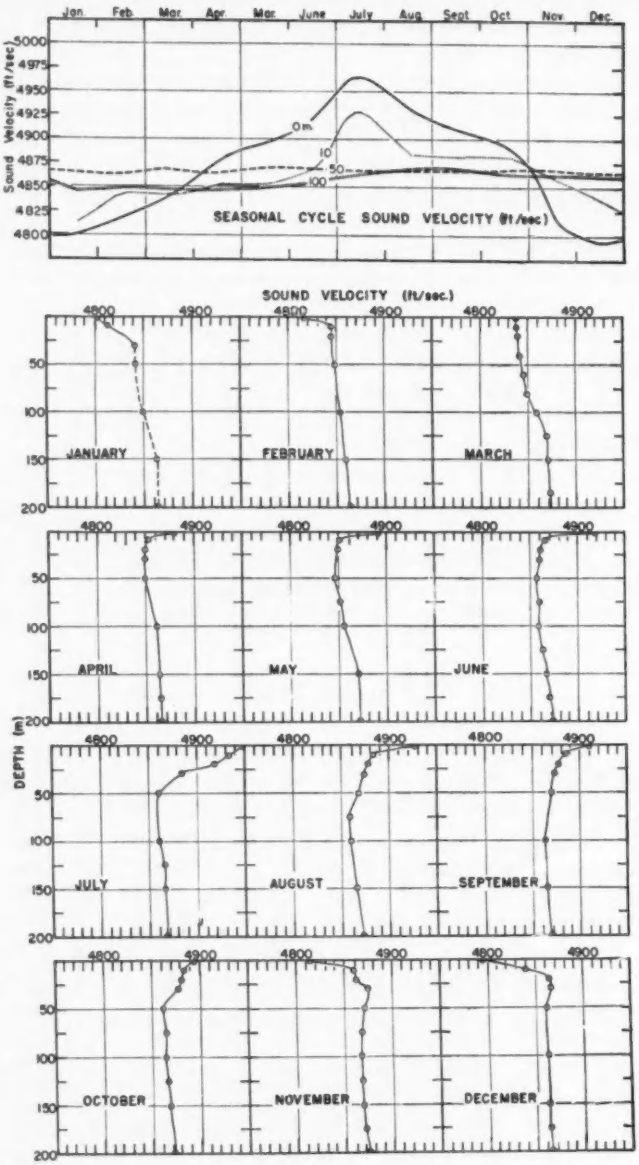

FIG. 19. Seasonal cycle of sound velocity at selected depths, and the corresponding mean monthly structures at Sta. J in Saanich Inlet, from mean values of data, 1931 to 1960.

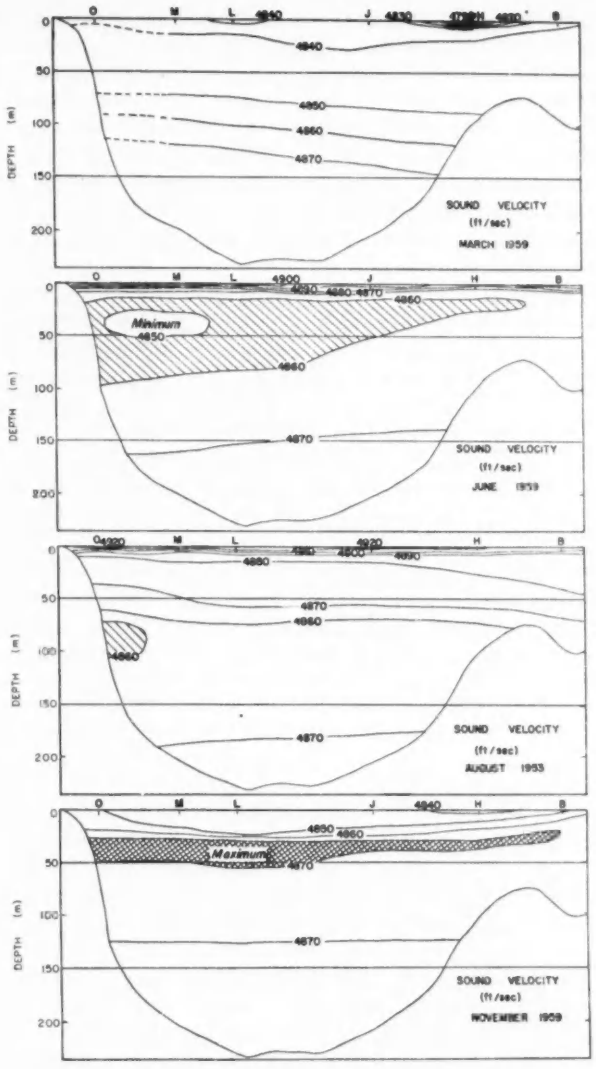

FIG. 20. Sound velocity structures in a longitudinal section of Saanich Inlet, calculated from observed data.

Observations were made in Haro Strait and Saanich Inlet in July and November 1931 (not published) and monthly in Haro Strait through 1951 and 1952 (Joint Committee on Oceanography, MS, 1955). Examination showed that the data collected in 1931 were comparable, at subsurface depths (10 to 150 m),

with data collected during 1951–52. On this basis, the seasonal cycles of density computed from data collected in 1930–31 are presented in Fig. 23 along with the corresponding cycles in Haro Strait observed in 1951–52. In general, the waters in Haro Strait are always more dense than those at corresponding depths in Saanich Inlet. Hence the upper waters from Saanich Inlet must always tend seaward from the inlet through Haro Strait. Also there must be a compensating subsurface inflow, below the brackish zone, to provide the sea water required for entrainment. It follows that there must be a compensating inflow to the inlet in the deep water, near the sill depth, and that the waters above the sill depth are always being flushed.

It must be realized that, in this mechanism, the rate of flushing depends on the rate of inflow of light (fresh) water. The flow of the Goldstream River into the inlet is so small that it is not sufficient to prevent fresh water from the Cowichan River intruding through the entrance. Evidently the light (brackish) water from the Cowichan River intrudes into the inlet with the tidal circulation. Once there it generates an estuarine flushing mechanism.

This weak estuarine mechanism could not flush the deep basin of the inlet below the depth of the sill, because the compensating inflow of sea water cannot be greater than the demand for entrainment into the surface layers.

Sea Water Intrusion

If the waters in Haro Strait above the sill depth (75 m) become more dense than the waters below this depth in the inlet, they would cascade into the basin and displace the resident waters in Saanich Inlet. Figure 23 shows that such a condition could have occurred in March.

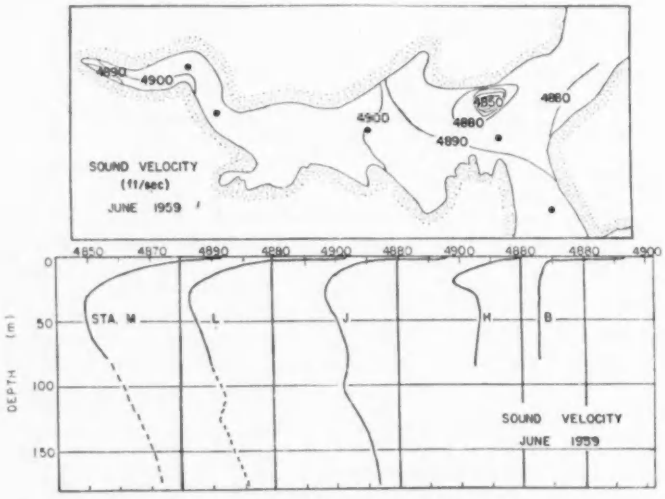

Fig. 21. Surface sound velocity and structures in Saanich Inlet, calculated from observed data.

Recalling the disparity in time between these data, they cannot be accepted as proof that such dense water intrusions (flushings) are of regular occurrence. It is assumed, although it has never been observed, that from time to time there is an intrusion of dense (well oxygenated) water from the mixing region in Haro Strait (Waldichuk, 1957) and consequently into Satellite Channel, and that some of this water could cascade over the sill into the basin of Saanich Inlet. There, its presence would be noted by a refreshment of the oxygen content (Fig. 17). In the basin it would be gradually diluted with the less dense upper water, probably by tidal oscillation, so that its density would decrease. Also its oxygen content would be utilized. Eventually, there would be another intrusion of dense water and another flushing. Such a process offers a plausible explanation for the observed facts (Fig. 17), because it could occur several times in quick succession, or be absent for several years.

Tidal Oscillation

It is notable in the seasonal longitudinal sections of the several properties (Fig. 5, 10, 14, 17 and 20) that in some cases the isopleths slope downward toward the mouth, and in others they slope upward. In the time-series observations (Fig. 8, Table I) the values of the properties tend to increase or decrease during the periods (22 to 32 hours). This suggests that the isopleths may have been rising or falling (oscillating) during the observations. However, these data are not adequate to determine if these changes of slope are seasonal or more frequent. Tully (1949) observed similar behaviour in Alberni Inlet where the observations were more frequent. He concluded that in such basins there were oscillations in the deep water, generated by the tidal movements above the sill depth. Elementary computations indicate that the natural period of internal oscillation in Saanich Inlet would be about 3.8 days.

INTERMEDIATE ECHO-SCATTERING LAYER

An intermediate echo-scattering layer in Saanich Inlet was recognized in the autumn of 1959 during an oceanographic survey of the inlet (Herlinveaux *et al.*, MS, 1960). Since then it has been observed several times during September through November. It is believed to be a permanent feature, although it has not been observed in the other seasons.

Figure 24 shows photo-copies of the echo records produced by an Edo sounding machine. The top one was made during a longitudinal traverse of the inlet from the entrance to the head (Nov. 16, 1959). The middle one was made while at anchor at Sta. J throughout the next day. The bottom one shows the echo-gram from a longitudinal traverse made almost a year later (October 17, 1960).

During the daylight hours the layer remained at a relatively constant depth but varied in thickness from 15 to 27 fm (27 to 50 m) and the depth of its upper limit varied between 34 and 47 fm (59 and 86 m). From the November 16, 1959, data it appeared that an upward migration took place at dusk between 1743

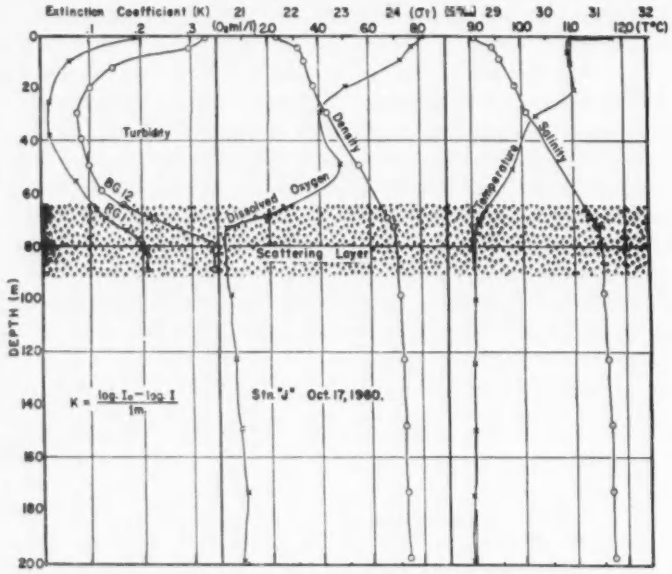

FIG. 22. Observed structures of turbidity, density (σ_t), dissolved oxygen, salinity, and temperature at Sta. J in Saanich Inlet.

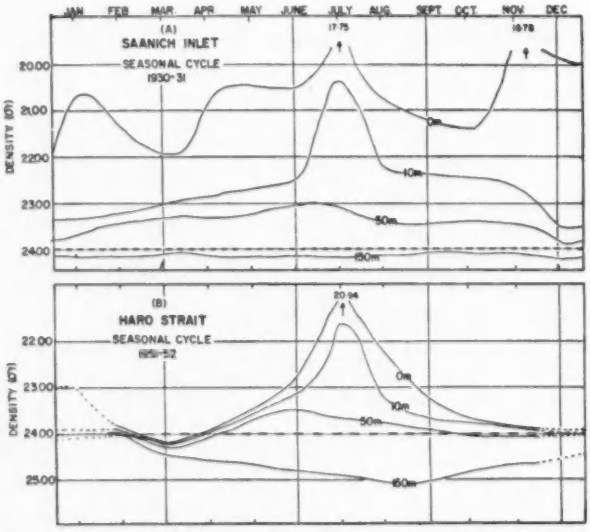

FIG. 23. Observed seasonal cycle of density (σ_t) at selected depths in Saanich Inlet (Sta. D) (1930–31) and in Haro Strait (Sta. B) (1951–52).

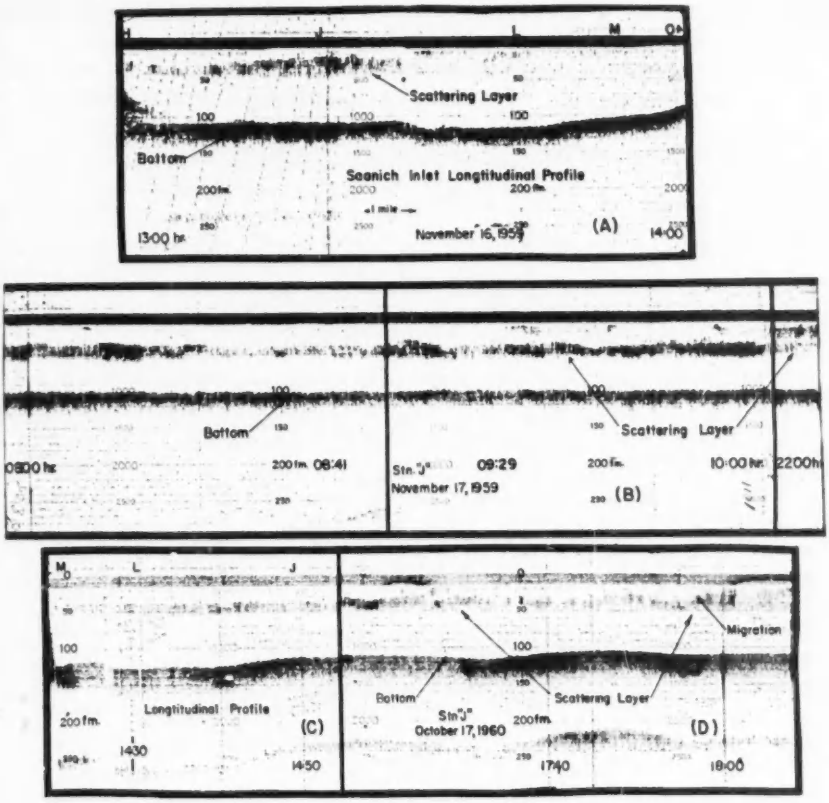

FIG. 24. Recordings from echo soundings in Saanich Inlet (Edo sounding machine).

and 1803 hours. Prior to this migration, the undulations and intensity of the scattering layer became erratic.

The scatterers comprising the layer were not identified during the 1959 survey because suitable fishing gear was not available. However, on October 17, 1960, the echo layer (Fig. 24) was fished by a midwater trawl (Barraclough and. Johnson, 1960) from one vessel (M.V. *A.P. Knight*) while another vessel (C.N. A.V. *Oshawa*) observed the echo layer and took oceanographic observations and plankton samples.

The midwater trawl first fished the scattering layer with the aid of a depth-determining device for approximately 72 minutes. It yielded 800 lb (400 kg) hake (*Merluccius productus*, 60–75 cm), 12 dogfish (*Squalus suckleyi*, 50–55 cm), 40 juvenile herring (*Clupea pallasii*, 75–100 cm), 4 whiting (*Theragra chalcogramma*, 60–70 cm) and 1 rockfish (*Sebastodes* sp., 30 cm). The trawl was then set at mid-depth (18–22 fm, 33–40 m) between the surface and the scattering

layer. It fished for 25 minutes and yielded 4 dogfish, 1 juvenile herring and 1 large pinkish jellyfish (*Cyanea capillata*) but no hake.

From these two trawls it appeared that hake and possibly whiting frequented the scattering layer by day, while dogfish and juvenile herring and jellyfish were

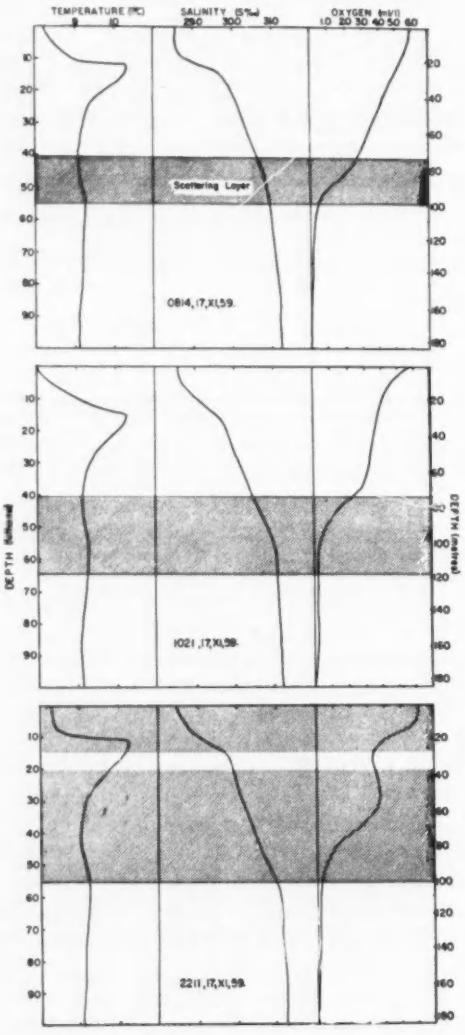

FIG. 25. Observed temperature, salinity, and dissolved oxygen structures and position of the echo scattering layer in Saanich Inlet. These data were observed at the same time as the echo-grams shown in Fig. 24.

found from the scattering layer to near the surface. The scattering layer stayed at a relatively constant depth all day. Since there was nothing in the stomachs of the fish caught then, it may be assumed that the fish were relatively inactive during the day. The evening dispersion of the echo-scattering layer towards the surface shown in Fig. 24 is a result of the fish moving upwards, probably to feed on the Euphausids which ascended as the light intensity diminished.

The properties of the water were observed coincidently with the echo-scattering layer on each occasion (Lane *et al.*, MS, 1960). Examples of these data are shown in Fig. 22 and 25. It appears that the scattering layer is associated with the bottom of the halocline, also the thermocline, and the deep oxycline.

The fish (hake) caught in the scattering layer by the midwater trawl all require dissolved oxygen from the water for respiration. Hence the lower limit of appreciable oxygen concentration would be the lower limit of the tolerable environment in Saanich Inlet.

The turbidity measurements shown in Fig. 22 indicate that the lower turbid layer coincides with the bottom of the scattering layer, and that the near-surface turbid layer, presumably due to algae, coincides with the upper limit of evening migration.

SUMMARY

1. The available information on values, distribution, and structures of temperature, salinity, temperature–salinity relations, density (σ_t), dissolved oxygen, and sound velocity in Saanich Inlet for each month of the year have been summarized and illustrated.
2. The waters above the sill depth (75 m) are normal and continuous with those in the approaches. The waters below sill depth are isolated from those in the approaches. The two regimes are separated by a halocline and oxycline but a thermocline is not always evident.
3. In all the structures there are ambient variations similar to those observed elsewhere in coastal waters.
4. In late winter the temperature gradients are positive. With the advent of spring and surface heating, a surface negative gradient is formed below which the temperature minimum persists until August. As the surface is cooled in autumn the remnants of the summer thermocline form a temperature maximum which persists until December.
5. The salinity structure is positive at all times. However, the surface salinity varies widely depending on the precipitation and local land drainage. In mid-summer, brackish water from the freshet of the Fraser River intrudes the inlet. There is a secondary halocline associated with the sill depth.
6. In summer there is a near-surface maximum of dissolved oxygen associated with photosynthesis of the large algae crops. There is an oxycline associated with the sill depth. Below this the waters are usually devoid of oxygen and sometimes contain hydrogen sulphide.

7. The sound-velocity structure is variable. In spring (March through July) there is a sound duct at intermediate depths. This vanishes in August when the structure becomes negative. Thereafter there is a sound-divergence zone which persists until December. In winter the structure is positive.
8. Above sill depth there is very weak estuarine and tidal flushing.
9. The deep basin is flushed sporadically when the waters above sill depth (75 m) in the approaches become more dense than the waters in the basin.
10. In the deep basin there appear to be tidally induced oscillations of period about 3.8 days.
11. There is an echo-scattering layer near the sill depth in the inlet. It contains concentrations of zooplankton and fish, and migrates toward the surface at dusk. The migration boundaries are limited by physical, chemical and biological barriers. The fish themselves provide spurious echoes to sound-ranging gear, and physical obstacles to underwater equipment.

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Physical Characteristics and Chemical Composition of Two Subspecies of Lake Trout[1,2]

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ABSTRACT

Trout taken from deep waters of Lake Superior are of two subspecies — a fat one and a lean one — that vary greatly from each other in physical characteristics and in chemical composition. The fat species has a smaller head, larger body, and lighter colour. The percentage of oil does not reach 20% in the fillets of the lean species, whereas it may reach 67% in fillets of the fat species, which has the highest known oil content of any fish.

COMPARISON OF SPECIES

Trout (*Cristivomer namaycush*) captured in Lake Superior vary greatly in amount of fatty constituents ("oil") and fishermen have long recognized the presence of two distinct varieties: the regular or "lean" trout, and the unusually fat type called "fats". These varieties have recently been accepted by biologists as representing two distinct subspecies: *Cristivomer* (or *Salvelinus*) *namaycush namaycush* and *Cristivomer namaycush siscowet*, respectively (Eschmeyer, 1957b; Hubbs and Lagler, 1949; Slastenenko, 1958).

Siscowet has smaller head, larger body, lighter colour, larger scales, and much higher content of oil than has *namaycush* (Fig. 1). Fishermen have taken individuals of both species weighing more than 23 kg (50 lb) and estimated to be as much as 20 years old. The best catches of *siscowets* are made at depths of 80 to 100 fathoms (150 to 180 m). They are however, sometimes caught near the surface at night during June and July when the temperature of the water has risen to about 40°F (4.5°C). The fish apparently come up to feed on flies, bees, and millers floating on the surface. The stomachs of specimens caught at the surface have been found to contain these insects as well as undigested bottom fish (private communication to the author by Stanley Sivertson of Sivertson Bros. Fisheries, Duluth, Minn., 1960).

Another unusual feature of *siscowets* is that they do not "blow up" when taken from depths of 100 fathoms, whereas *namaycush* captured at even 40

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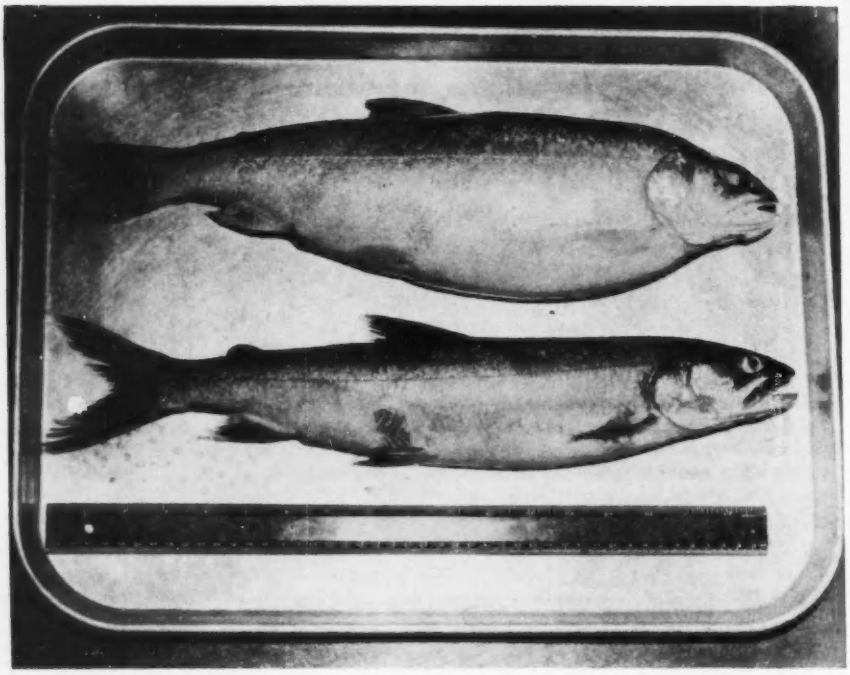

FIG. 1. Fat and lean trout.

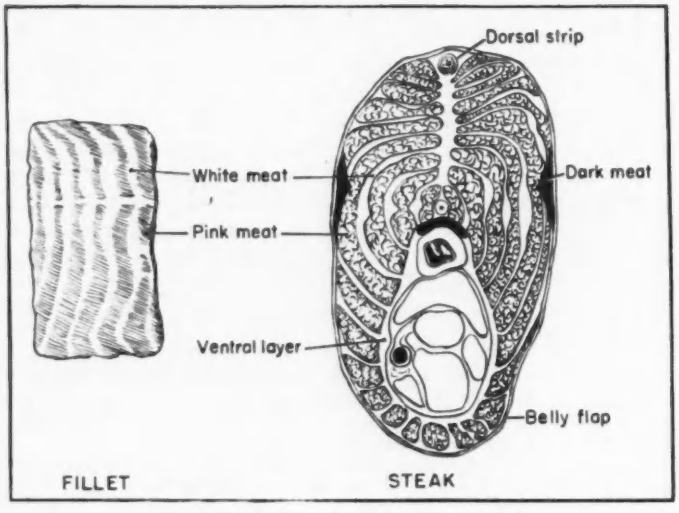

FIG. 2. Fillet and steak sections of fat trout.

fathoms are ready to burst when brought to the surface. This difference might be due to the small size of the visceral cavity. *Siscowets* have very little room in their stomachs for food. The amount present represents a small fraction of that found in the stomach of a *namaycush* of the same size. Frequently, fishermen find very little, if anything, but pure fat lining the stomach wall of the larger *siscowets*. Thus the very high fat content of the species cannot be attributed to excessive eating.

Before the invasion of sea lampreys, which almost depleted both subspecies of trout, some fishermen specialized in *siscowet* fishing. Two men in a 35-foot boat, using gill nets, could take up to 40,000 lb (18,000 kg) of these fish in a season. The *siscowets* sold for about the same price as lean trout (25 to 40 cents per pound). The entire catch was frozen and then smoked. *Siscowets* were usually not marketed in the Great Lakes area but were shipped to the East Coast for sale to special consumers.

DESCRIPTION OF SPECIMENS

In order that the physical and chemical differences between the two subspecies could be studied, several series of each were obtained from the deep waters of Lake Superior during the summers of 1952, 1954, 1957, and 1959. All of the specimens were shipped in ice, in the round, to Seattle, where the samples were prepared for analysis. The fish, if not processed at once, were frozen and held at −18°C until they could be processed.

All of the specimens were small to medium. Table I presents the ranges and average values for lengths and weights of the specimens of the two subspecies.

TABLE I. Physical data for lake trout.

Type	Series No.	No. of fish	Date of capture	Length		Weight	
				Av.	Range	Av.	Range
				centimetres		*kilograms*	
Namaycush	1	12	June 1952				
	2	3	Aug. 1954	63	50–73	2.80	1.19–3.91
	3	5	Sept. 1954	41	35–49	1.05	0.61–1.85
	5	3	Aug. 1960	44	40–48	1.00	0.70–1.45
	Total:	23	Average:	49	35–73	1.62	0.61–3.91
Siscowet	3	10	Sept. 1954	60	39–82	3.42	0.95–9.55
	4	10	June 1959	62	54–69	3.30	1.94–4.44
	5	9	Aug. 1960	62	39–69	4.38	0.93–7.36
	Total:	29	Average:	61	39–82	3.70	0.93–9.55

PREPARATION OF SAMPLES

The specific parts used for analysis included: nape, center, and tail steak sections; whole fillets; dark meat (lateral dark muscle); light meat (including pink and white layers from one specimen); belly flaps; dorsal strip; and ventral layer (Fig. 2). The ventral layer is a deposit of fat, having about the consistency of lard. It surrounds the viscera and lies between the visceral lining and the ribs. Each part to be analyzed, after being removed from the cold (thawed, if frozen) freshly washed fish, was separated from bones, skin, and loose scales; ground or chopped to a nearly homogeneous state; vacuum sealed in ¼-lb fish cans; frozen, and then held at −18°C until analyzed. Prior to analysis, the cans containing the samples were immersed in lukewarm water for 15 minutes, after which the partially thawed contents were removed and ground to homogeneity with a high-speed cutting blade.

EXPERIMENTAL PROCEDURE

The six constituents—moisture, protein, oil, ash, sodium (Na^+), and potassium (K^+)—were determined by standard methods of the Association of Official Agricultural Chemists (1960). Moisture was determined by difference in weight after heating the sample in a forced-draft air oven at 103 ± 2°C. Total protein was determined by the Kjeldahl procedure, using the factor $N \times 6.25$. Oil was separated by solvent extraction following acid hydrolysis. Ash was calculated from the difference in weight after ignition in a muffle furnace at 525 ± 10°C. Analyses for Na^+ and K^+ were made with a flame photometer from solutions prepared by dissolving the sample of ash in a nitric acid solution made by diluting the concentrated acid with 9 volumes of water.

RESULTS AND DISCUSSION

The differences in the composition of lean and fat lake trout and the variations within each species are shown in Table II. The 23 lean trout fillets had the following average composition: moisture 73.0%, protein 18.0%, oil 9.4%, and ash 1.0%. Only three individuals of this species were analyzed for Na^+ and K^+. The average values for these three were Na^+ 31 mg%, and K^+ 300 mg%. Of the constituents analyzed, oil showed the greatest variation, ranging from 2 to 22%. Lower values were found in the smaller specimens, but the variation was not uniformly proportional to size. The belly flaps of one specimen, whose fillets had an oil content of 3%, analyzed 20% oil.

Large variations were found in the *siscowet* fillets. The average composition of fillets from 29 fish was moisture 41.4%, protein 9.6%, oil 48.5%, ash 0.6%, Na^+ 27 mg%, and K^+ 165 mg%. The protein and oil contents varied inversely, ranging from 6.1 to 15.9% and from 67.2 to 21.3%, respectively. The dark meat of the fillets was much higher in oil than was the light meat, averaging 66.7% in contrast to 39.6% in the light meat. In one specimen, the white and pink layers of the light meat were separated and analyzed for oil. The percentages of oil were 61.0 for the white and 38.5 for the pink.

TABLE II. Variations in the composition of lake trout fillets.

Series No.	No. of fish		Moisture		Protein		Oil		Ash		Na^+		K^+	
			Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range	Av.	Range
			percent		*percent*		*percent*		*percent*		*mg%*		*mg%*	
A. Namaycush fillets														
1	12		72.0	64.3–80.3	18.1	15.8–19.6	10.2	1.9–19.4	1.03	0.84–1.13				
2	3		70.8	65.3–74.0	20.0	19.1–20.8	9.3	5.2–14.1	1.15	0.94–1.30				
3	5		70.5	65.1–74.8	16.0	14.8–17.8	14.5	9.1–22.5	1.01	0.84–1.18				
5	3		78.8	76.5–81.4	17.6	15.7–18.8	3.7	3.1– 4.8	0.87	0.77–0.94	31	18–40	300	291–312
	23	Av.:	73.0	64.3–81.4	18.0	14.8–20.8	9.4	1.9–22.5	1.02	0.77–1.30				
B. Siscowet fillets														
3	10		43.4	27.8–59.0	9.0	6.7–11.9	46.8	27.3–64.2	0.60	0.41–0.80				
4	10		42.4	27.4–63.3	10.2	6.1–15.9	47.3	21.3–67.2	0.54	0.35–0.82	31	22–49	165	93–270
5	9		38.3	26.8–54.5	9.6	6.2–13.0	51.4	33.2–66.1	0.60	0.38–0.85	22	16–30	164	102–224
	29	Av.:	41.4	26.8–63.3	9.6	6.1–15.9	48.5	21.3–67.2	0.58	0.35–0.85	27	16–49	165	93–270
C. Siscowet parts														
4	10	Light	48.1	33.2–62.8	12.1	7.3–15.9	39.6	21.9–58.7	0.66	0.44–0.85	31	26–35	207	130–278
		Dark					66.7	59.9–70.9						
		N*	36.7	27.4–51.8	8.6	6.1–12.2	54.9	35.4–67.2	0.46	0.35–0.62	26	22–30	139	93–193
		C	37.6	30.1–53.4	9.1	6.8–12.9	53.0	33.4–62.8	0.51	0.40–0.69	27	22–31	155	107–223
		T	52.9	44.6–63.3	12.9	9.9–15.9	33.9	21.3–44.9	0.66	0.58–0.82	40	31–49	204	154–270
		Av.:	42.4	27.4–63.3	10.2	6.1–15.9	47.3	21.3–67.2	0.54	0.35–0.82	31	22–49	165	93–270
5	9	N	36.4	26.8–49.1	9.2	6.2–12.6	54.1	38.6–66.1	0.56	0.38–0.79	21	16–27	155	102–216
		C	35.1	30.2–44.9	9.2	7.9–11.3	55.1	44.4–61.2	0.58	0.48–0.71	20	16–25	156	131–196
		T	43.4	36.5–54.5	10.6	9.5–13.0	46.0	33.2–53.9	0.66	0.55–0.85	25	21–30	181	145–224
		Av.:	38.3	26.8–54.5	9.6	6.2–13.0	51.7	33.2–66.1	0.60	0.38–0.85	22	16–30	164	102–224
	4	Bf	15.2	10.4–28.4	4.9	4.2– 5.8	74.5	65.2–85.7	0.23	0.16–0.27	16	12–22	71	37– 68
	3	Do	10.0	8.7–12.0	2.6	2.4– 2.8	86.2	82.9–88.4	0.19	0.18–0.20	10	10–10	55	42– 76
	7	Ve	8.6	0.7–16.0	1.8	0.7– 2.4	89.0	81.5–97.0	0.13	0.06–0.19	15	8–26	43	21– 80

*N, C, and T refer to nape, center, and tail. Bf, Do, and Ve refer to belly flap, dorsal, and ventral parts.

A comparison of the composition of the nape, center, and tail sections of the *siscowets* showed a much higher content of protein and lower content of oil in the tail than in the nape part, but there was not much difference between the nape and center for either constituent. The highest values for both Na^+ and K^+ were found in the tail sections.

Belly flaps and dorsal and ventral parts were very high in oil, averaging 74.5, 86.2, and 89.0%, respectively. The lowest value was 65.2% for one of the belly flap samples, and the highest was 97.0% for a ventral sample. The amounts of other constituents in this latter sample were moisture 0.7%, protein 0.7%, ash 0.06%, Na^+ 8 mg%, and K^+ 21 mg%.

The content of oil in the fillets increased greatly with increasing size of *siscowets* (Table III). In fish of series 5 (Table II) the range was from 27.3% for a 1-kg specimen to 63.5% for a 10 kg one. The increase was quite uniform.

Oil samples from two of the specimens were analyzed for fatty acids by gas chromatography. The distribution with regard to chain length and the extent of unsaturation did not reveal any unusual or outstanding characteristics. One of the samples was analyzed for PO_4 and showed no measurable amount of this constituent.

Sex and sexual maturity were determined for the fish in series 5. All were sexually immature, and most of them were females. There was no great difference in composition that could be attributed to sex.

TABLE III. Variation in composition of *siscowet* fillets with size of fish. (Includes series 2, 3 and 5.)

Size	No. of fish	Length	Weight	Moisture	Protein	Oil	Ash	Na^+	K^+
kg		*cm*	*kg*	%	%	%	%	*mg%*	*mg%*
1– 2	10	47	1.5	54.7	12.1	33.0	0.66	30	236
2– 5	13	62	3.3	40.1	9.2	49.9	0.57	30	159
5–10	6	71	6.1	32.1	7.9	59.4	0.51	19	152

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of Dave H. Wieg and Mable A. Edwards of this Laboratory in preparation and analysis of samples and in tabulation of data. The drawing for Fig. 2 was prepared by Virginia Coleman.

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A Review of the Temperature and Salinity Structures in the Approaches to Vancouver Island, British Columbia[1]

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. ABSTRACT

Oceanographic data gathered along the west coast of Vancouver Island since 1933 have been examined in an effort to derive an appreciation of oceanographic processes in this region.

One area, which was the source of most data, was chosen as representative for the study, principally to satisfy continuity and partly to offset the tendency to use isolated sets of data as examples of "typical" coastal structure under rather general circumstances.

The temperature and salinity structures and distributions are revealed as basically being functions of fresh water input, insolation, wind, and the ocean influence. The local climate is outlined, and some pertinent physical processes are reviewed, prior to a generalized description of the coastal oceanographic system.

Predominant northwest winds and local runoff result in a shallow (20 to 40 m) springtime halocline in coastal waters. Summer insolation and the resulting stability of the thermocline, coincident with the halocline, limit the depth of mixing so that the summer runoff from mainland sources is mainly preserved in the shallow (10 to 20 m) upper zone of the salinity structure.

Intermittent wind-induced divergence and an entrainment demand is offered as reason for the occurrence of cold, saline bottom water in this region during the summer.

Autumnal cooling and southeasterly winds destroy the vertical structures and result in a near-shore accumulation of dilute surface water in winter. Relatively warm bottom temperatures offer evidence of a winter convergence, or relaxation of the divergence mechanism.

Coastal oceanographic structures are often dominated by short-term variabilities. The significance of these is demonstrated by the ranges of variation obtained during time-series observations.

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I. INTRODUCTION

DURING RECENT YEARS considerable progress has been made in defining the oceanographic structures and mechanisms in the inland seaways of British Columbia and in the offshore oceanic regions. However, relatively little progress has been made in resolving these features along the ocean coast.

The coastal region is that which overlies the continental shelf and slope. As shown in Fig. 1, the depth of the continental shelf along the British Columbia coast is generally less than 200 m. It is widest off Juan de Fuca Strait, at the

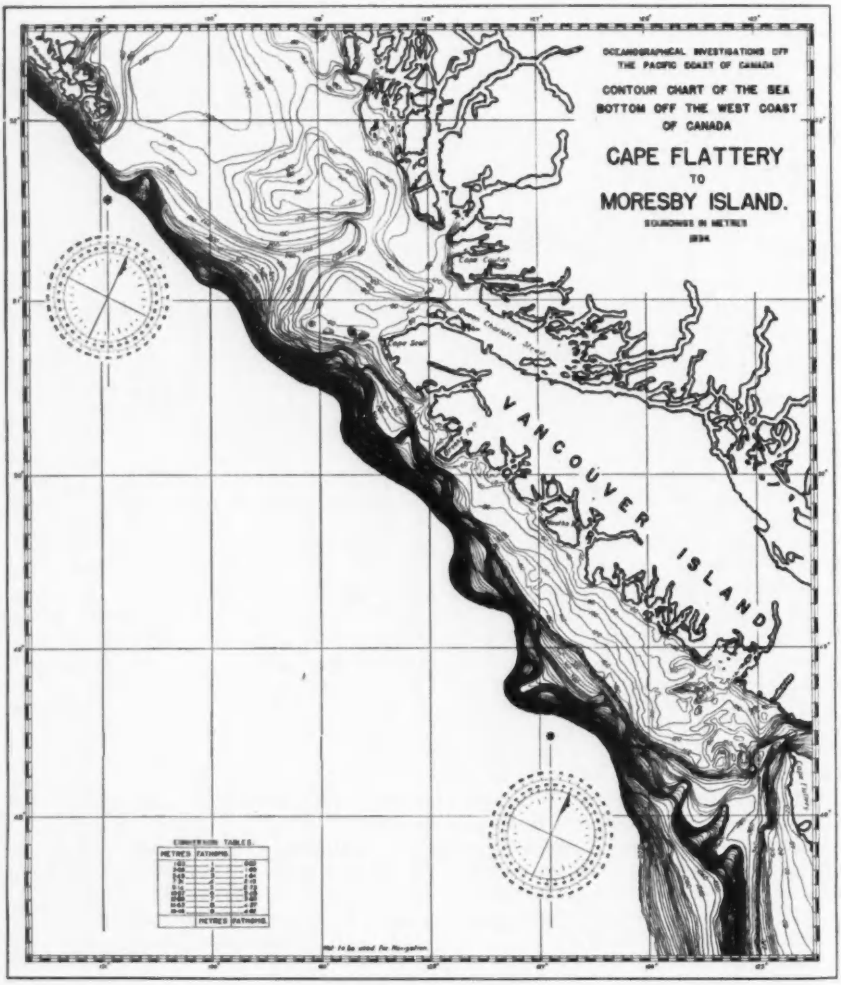

FIG. 1. Contour chart of the sea bottom from Cape Flattery to Moresby Island, B.C.

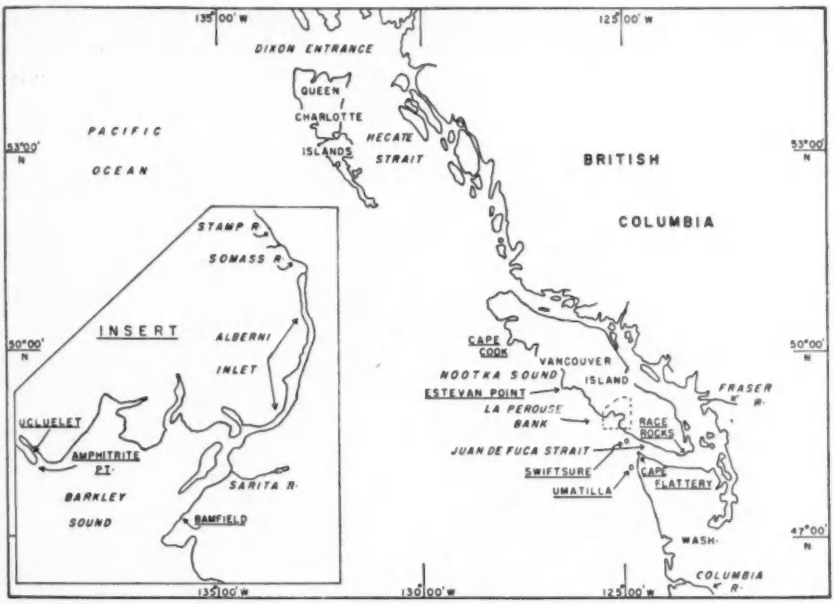

FIG. 2. Coastal locations referred to in the text.

southern end of Vancouver Island. It narrows northward and virtually vanishes off the Queen Charlotte Islands. The continental slope "drops off" to more than 2000 m depth.

Beginning with a study of Nootka Sound in 1933 (Tully, 1937) Canadian oceanographers have carried out several investigations in this coastal region (see Fig. 2 for all locations mentioned both here and in subsequent sections). Many of these investigations were localized studies, while others attempted to define and describe the more general distributions in the coastal waters.

The local studies include those in Nootka Sound (1933), Barkley Sound (1937, 1950, 1953), the approaches to Juan de Fuca Strait (1937, 1938), Dixon Entrance (1938), the Swiftsure area (1938), and in the area about La Perouse Bank (1960).

Those cruises operating in a more extensive area were the coastal surveys, which covered the shelf areas off Vancouver Island (1934, 1936), and off the Queen Charlotte Islands (1935); the Offshore Survey (1936), which operated seaward from the northern, central and southern portions of Vancouver Island; Projects Offshore (1950–1952) reported by Doe (1955); the Coastal Surveys (1957) which included the area from 46°N to 56°N to about 200 miles offshore; the Coastal Seaways cruises (1958, 1959), which monitored several lines of stations seaward of both Vancouver Island and the Queen Charlotte Islands; and the Seaways Program (1960–1961) which is a modification of the Coastal Seaway cruises.

The data from all these expeditions have been processed and most of them have been reported (Pacific Oceanographic Group, MSS, 1957–1960). These reports also include daily seawater observations of temperature and salinity from 21 locations along the British Columbia coast for varying periods, some since 1933.

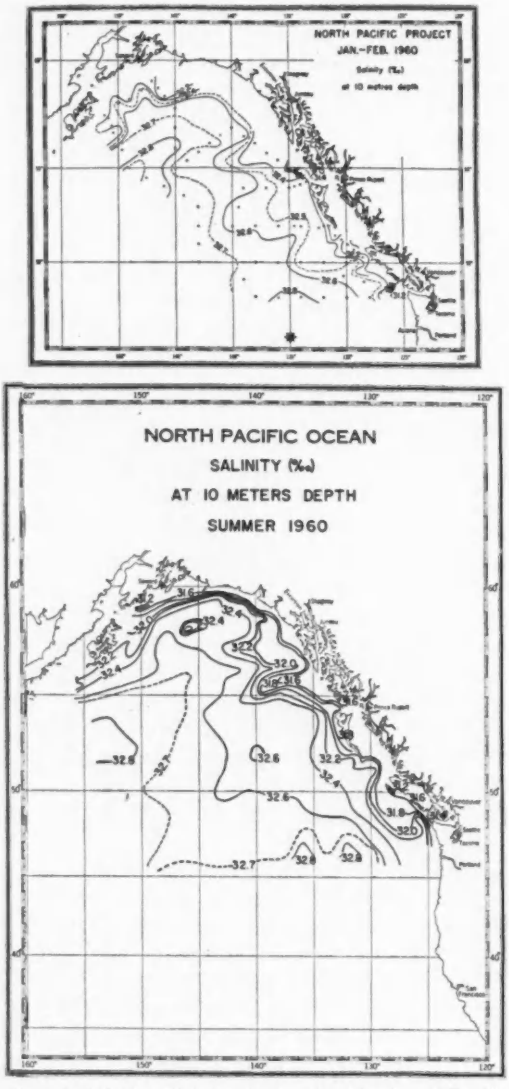

FIG. 3. Salinity distribution in the Northeast Pacific Ocean at 10 m depth in winter (upper) and summer (lower).

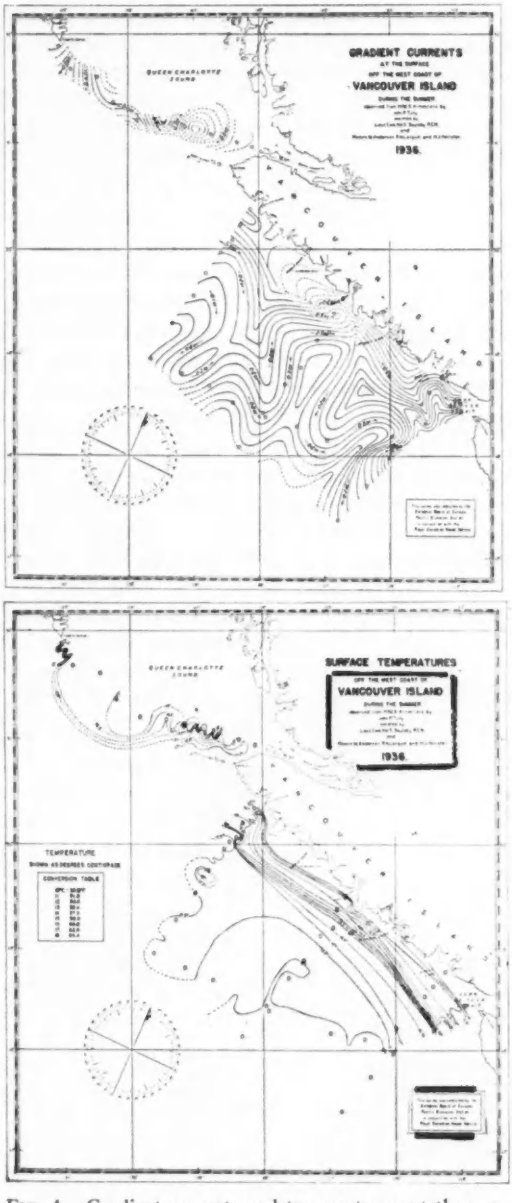

FIG. 4. Gradient currents and temperatures, at the surface, off the west coast of Vancouver Island in the summer of 1936. (After Tully, 1937.)

The meteorological data were taken from the records and publications of the Canada Department of Transport, Meteorological Division, (1957–1960) River discharge data were taken from records and publications of the Canada Department of Northern Affairs and National Resources, Water Resources Division, (1957–1959), and the United States Department of the Interior, Geological Survey, Water Resources Division, (1957–1959).

II. BACKGROUND INFORMATION

Characteristically, coastal waters are less saline than oceanic waters at corresponding depths. Figure 3 illustrates, for both winter and summer, such lower salinities and hence a conservation of fresh water along the coast from the significant volume of runoff from the adjacent land masses.

Tully (1937) interpreted summer data to show continuity of temperature and current parallel to the coast with a strong gradient to seaward (Fig. 4). In 1957, Barber reported successive lines of stations normal to the coast, and parallel to the coast. An interpretation of the temperature data is shown in Fig. 5. Coastwise continuity and a gradient to seaward have been assumed in accounting for the distribution in areas of sparse sampling. However, in areas of concentrated sampling, complex convolutions of isopleths are apparent. There are, evidently, considerable complexities superimposed on the general pictures.

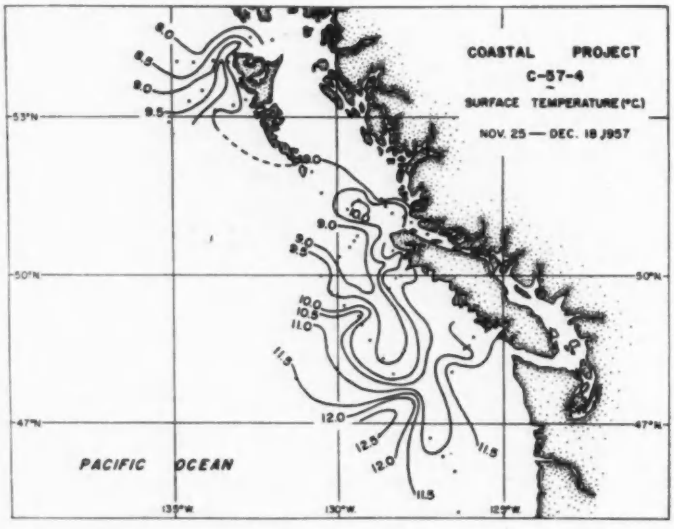

FIG. 5. Surface temperature distribution off the west coast of British Columbia in the late autumn of 1957.

Marmer (1926), Thompson and Van Cleve (1936), and Tully (1938) have shown that in winter a surface coastwise water movement to the north exists in the approaches to Juan de Fuca Strait. Barber (1957) observed a similar drift off the northern end of Vancouver Island. It was also shown in those discussions that the coastwise currents were small or absent in summer. It follows that convolutions of horizontal structure along Vancouver Island result from meanders of the coastwise drift, or discontinuities in the structure, or both.

Figures 6 and 7 respectively show vertical temperature and salinity seaward sections observed in corresponding months of two successive years. Although similar ranges of values and similar thermocline and halocline structures are evident in both years, differences in the depths and values of these features are apparent. Significant differences in horizontal continuity and distribution are also evident.

The surface temperature and salinity at Amphitrite Point are shown for three successive years in Fig. 8. These values are 7-day running averages of daily data. Aside from the ambient variations, significant differences are apparent from year to year. These differences, while significant in themselves, do not override the obvious seasonal cycle. It is reasoned that much of the differences observed in specific months during various years may be attributed to variations in the controlling factors from one year to the next.

Figure 9 shows two vertical temperature structures from a line of stations seaward from the southern side of Barkley Sound, observed on successive days during the rising tide. The changes of vertical structure, which are evident in this short time, cannot be attributed to seasonal variations.

From the examination of a large number of such data, it appears that the features of seaward and vertical gradients, and the coastwise continuity of water masses, are real in a general sense. However, there are considerable variations in short distances and short times which complicate and frequently negate the basic trend. It is not possible to assume simple continuity between widespread lines of observations, such as seaward from the southern, central and northern ends of Vancouver Island. Nor is it realistic to assume more than a first-order consistency of structure. Therefore, it was decided to refrain from co-ordinating horizontal distributions of properties (such as shown in Fig. 4 and 5) where the surveys required several weeks. Rather, it was decided to concentrate attention on the numerous data from a local area in the approaches to Barkley Sound (Fig. 2) and assess the variability and its relation to causative factors.

III. CAUSATIVE FACTORS

The factors directly influencing coastal waters are insolation, wind, precipitation, and tide. Precipitation is mainly an indirect factor, as it ultimately produces land drainage. The adjacent ocean, with its circulation and physical properties, necessarily is responsible for certain aspects of the coastal water's behaviour. Constantly superimposed on these factors is the effect of the Earth's

rotation, the Coriolis force which in the Northern Hemisphere acts to the right of the path of all moving bodies.

Since many of the causative factors are meteorological in origin, the annual cycle of their effects is recognized. In some cases, such as the wind, the complexity of the factors involved may result in short-term variations of prime importance.

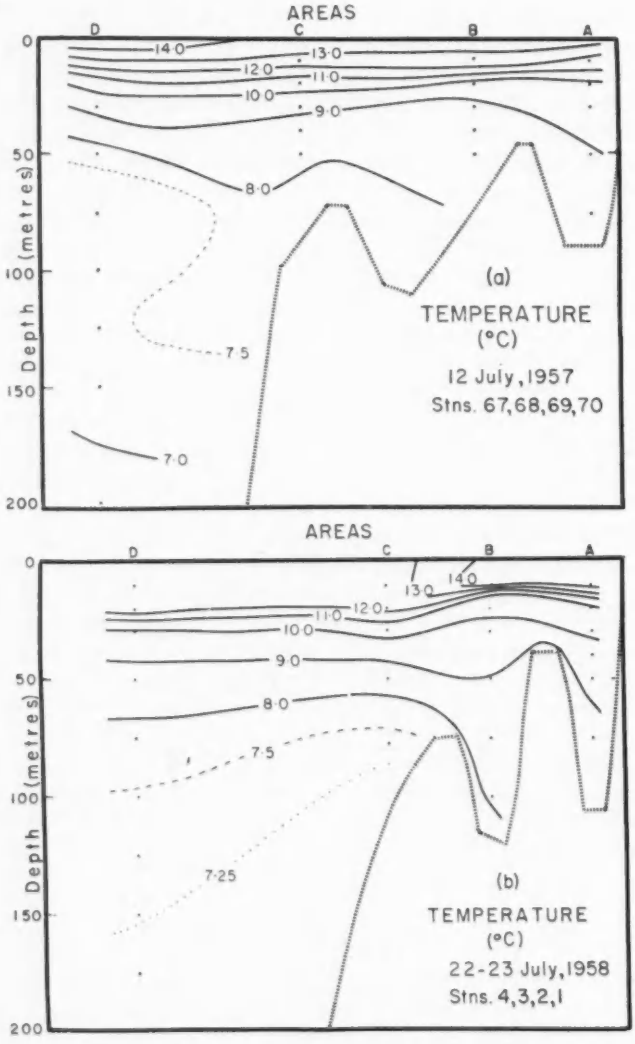

FIG. 6. Temperature structures July 1957 and July 1958 in a section seaward from Amphitrite Point (cf. Fig. 21).

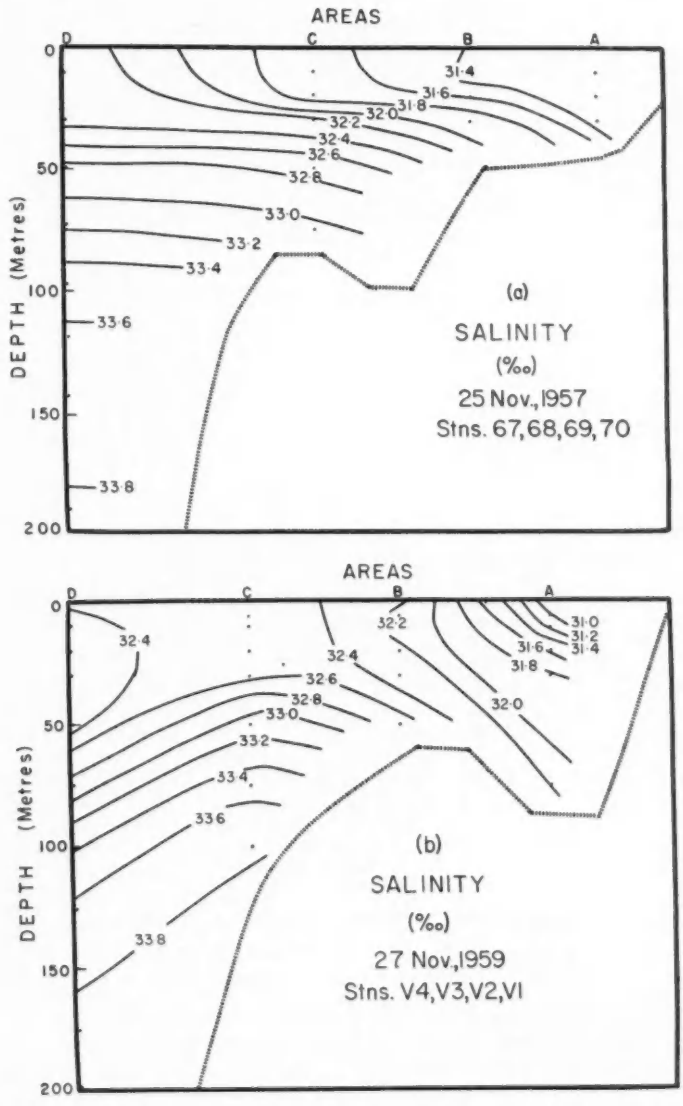

FIG. 7. Salinity structures November 1957 and November 1959 in a section seaward from Amphitrite Point (cf. Fig. 21).

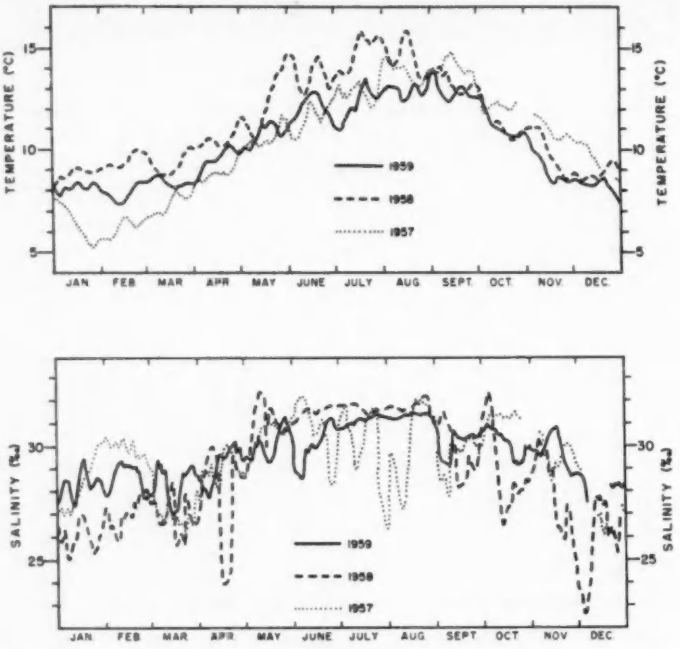

FIG. 8. Plot of 7-day running averages of temperature and salinity observed daily at Amphitrite Point (Fig. 2) 1957 through 1959.

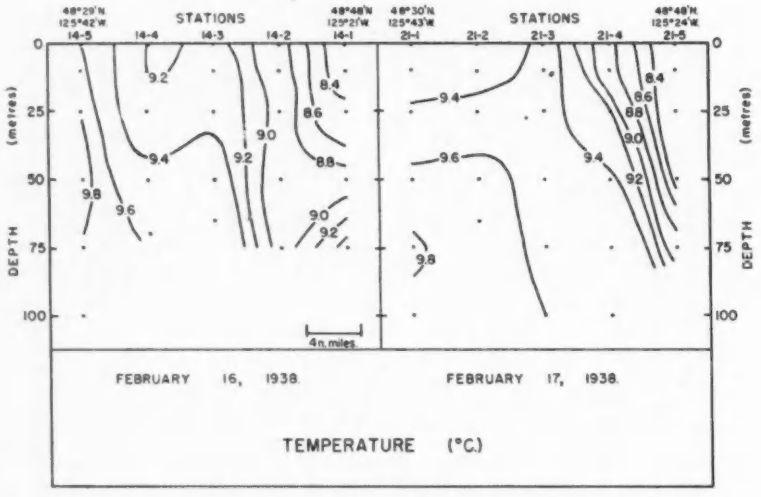

FIG. 9. Temperature structures observed one day apart in a common line of stations seaward of Barkley Sound, 1938.

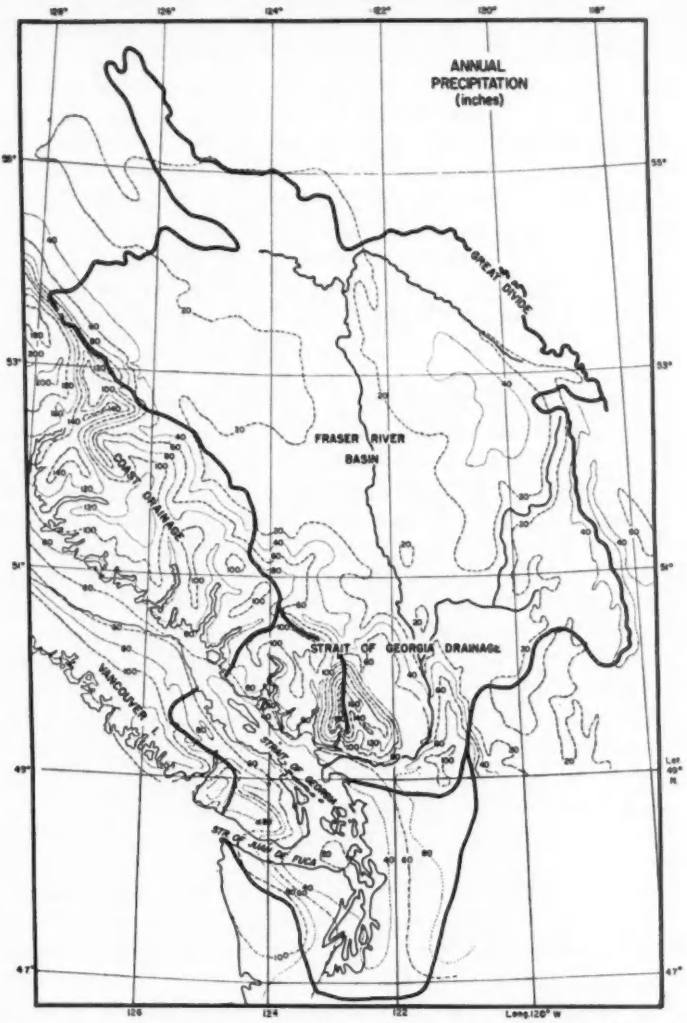

FIG. 10. Annual precipitation (inches) in the part of British Columbia which drains seaward through Juan de Fuca Strait.

A more orderly, daily or semi-daily, variation in properties may result from tidal forces, depending on the physical surroundings as well as the geographical location of the area being investigated.

A. Fresh Water Mechanisms

The considerable amount of rainfall in this region (greater than 100 inches (250 cm) per year, Fig. 10) dilutes the ocean waters both directly by rainfall and indirectly by land drainage into estuaries.

The mechanics of dilution from runoff have been studied by Tully (1949, 1952, 1958). He observed that the fresh water moved persistently seaward at the surface, entraining sea water from below to form a transition zone in which there was a halocline. Wind mixing usually created an isohaline upper zone. Below the halocline was a lower zone in which the vertical and horizontal gradients were small. This structure depends on there being an excess supply of fresh water.

A similar structure (on a larger scale) has been observed in the Subarctic Pacific Ocean and compared to the estuarine model (Tully and Barber, 1960). There the upper zone is about 100 m deep. The halocline occurs between 100 and 200 m depth and its lower limit usually occurs at salinity $33.8 \pm 0.1‰$. It is permanent throughout the year (Doe, 1955; Dodimead and Tully, 1958; Dodimead, MS, 1958).

The shallow estuarine upper zone discharges into the coastal waters where it forms a shallow estuarine structure in the upper zone of the oceanic waters. Hence over the continental shelf there may exist, in order of depth, an isohaline surface layer, an estuarine halocline, a residual portion of the oceanic upper zone, the oceanic halocline, and if the depth permits, a portion of the oceanic lower zone.

In this region the oceanic upper zone, created by surface mixing processes, will lose its identity when an estuarine structure is established above it. The oceanic halocline will be entrained and in the limit will comprise the entire zone between the estuarine halocline and the oceanic lower zone.

Hence, the coastal salinity structure is a function of the estuarine structure on the one side, of the oceanic structure on the other, and of their respective characteristics.

Considerable variation results from the alternating influences of these boundary regions. In the coastal region, the shallow estuarine structure is most apparent from spring through summer. During this period surface salinities vary considerably (Fig. 8). During the winter period, because of the winds, oceanic structures dominate in the region, and the shallow estuarine structure vanishes.

The shallow estuarine structure is a consequence of land drainage, which in turn is a consequence of precipitation, modified by snow storage. The average monthly precipitation at Bamfield, B.C., in shown in Fig. 11. There is clearly a winter (December–January) maximum and summer (April–August) minimum. The extremes indicate that there are large ranges in individual months.

Pickard and McLeod (1953) and Herlinveaux and Tully (1961) have noted that runoff from the lower levels of Vancouver Island is nearly coincident with the precipitation and is greatest in winter. Figure 12 shows precipitation at Bamfield along with the runoff from the Sarita and Stamp Rivers. The Sarita River follows the precipitation pattern quite closely, while the Stamp, representing the higher-altitude interior rivers, shows a secondary peak in the early summer. This is due to the melting of the winter snow storage in May and June. These reach the sea through Barkley Sound and are the prime local sources of fresh water. The surface salinity values recorded at Amphitrite Lightstation through 1956 and 1957 are also shown in Fig. 12.

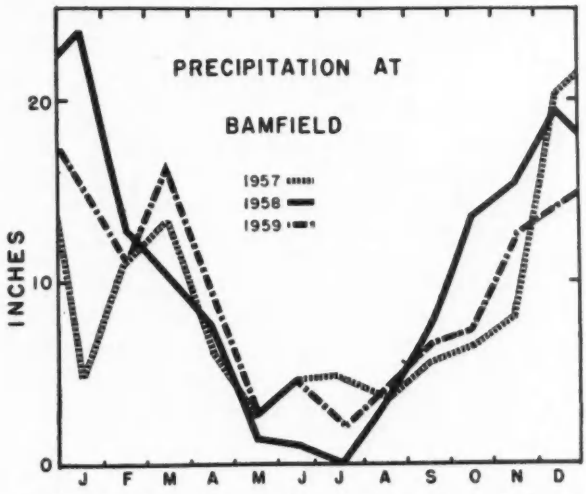

FIG. 11. Precipitation recorded at Bamfield, B.C., (1957 through 1959).

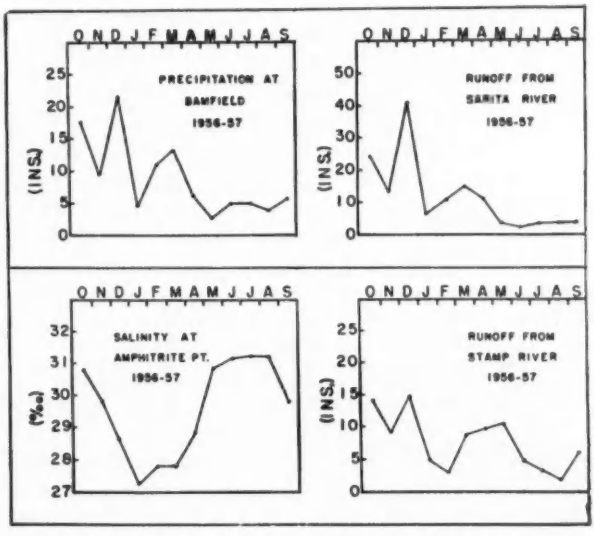

FIG. 12. Precipitation at Bamfield, B.C.; surface salinity at Amphitrite Point; and runoff from the Sarita River and Stamp River; for the water-year period, October through September, 1956–1957.

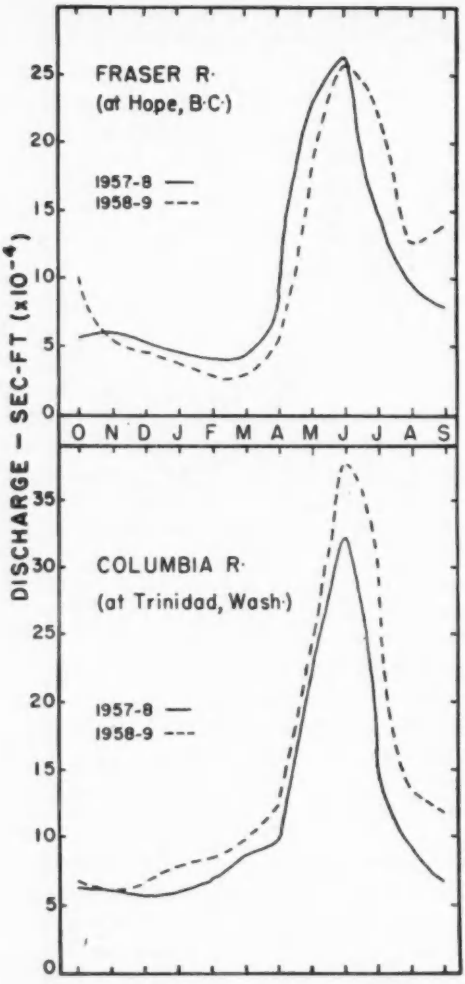

FIG. 13. Average monthly discharge from the Fraser River and the Columbia River (1957 through 1959).

Snow storage is the prime factor in the discharge from the high-level mainland sources (Fraser and Columbia Rivers). Juan de Fuca Strait, bearing the summer peak runoff from the Fraser River (Fig. 13), is a major source of dilute water in, and immediately northward of the approaches to Juan de Fuca Strait (Herlinveaux and Tully, 1961; Tully, 1942). Also it is possible that the considerable spring discharge from the Columbia River (Fig. 13) may occasionally move northward along the coast, at least as far as Juan de Fuca Strait.

The net effect is that the fresh water supply to the coastal region off southern Vancouver Island is greatest in spring (April–June) and defines the period of dominance of estuarine structure.

B. Insolation

The relation between the temperature structure found in sea waters and the seasonal variations of insolation have been studied on many scales (cf. e.g. Doe, 1955; Tully, 1950, 1956; Tabata, 1958, 1961; Dodimead, MS, 1958). It has been found that seasonal surface warming in the ocean creates a structure generally consisting of a mixed layer; a thermocline, or, in some cases, a series of two or more thermoclines; and a subthermocline zone (Fig. 14). Each temperature increment is due to surface heating and is transferred downward as small transient thermoclines through the otherwise mixed (isothermal) layer, to the limiting depth of wind influence (Tully *et al.*, 1961). There the main thermocline is formed and grows throughout the heating season. When surface cooling exceeds warming, and the storm frequency increases, the net loss of heat results in the deepening and decay of the thermocline through the seasons as observed (Fig. 15) at Ocean Weather Station "P" (Lat. 50°N, Long. 145°W) in the mid-northeastern Pacific.

A number of authors (cf. e.g. Tully and Dodimead, 1957; Waldichuck, 1957; Tabata and Pickard, 1957; Herlinveaux and Tully, 1961) have observed that the summer thermocline and shallow halocline are coincident in coastal seaways. From the available data this appears to be true in coastal waters as well. However, in the ocean the thermocline is developed and decays wholly within the oceanic upper zone (Dodimead, 1961) and is independent of the permanent halocline.

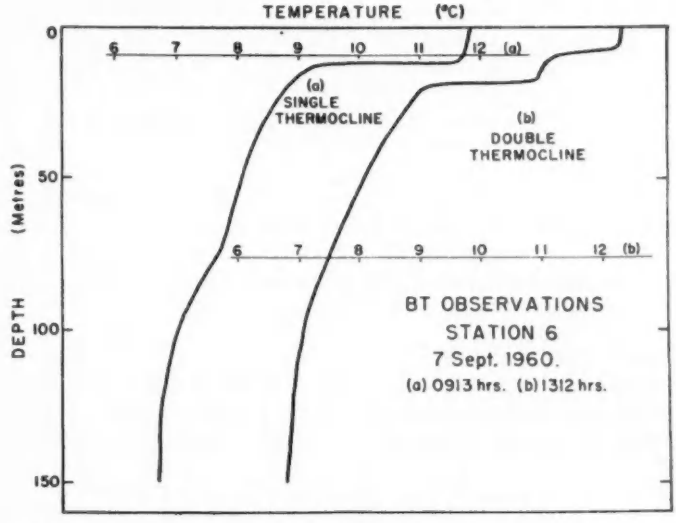

Fig. 14. Examples of single and double thermocline structures in coastal waters.

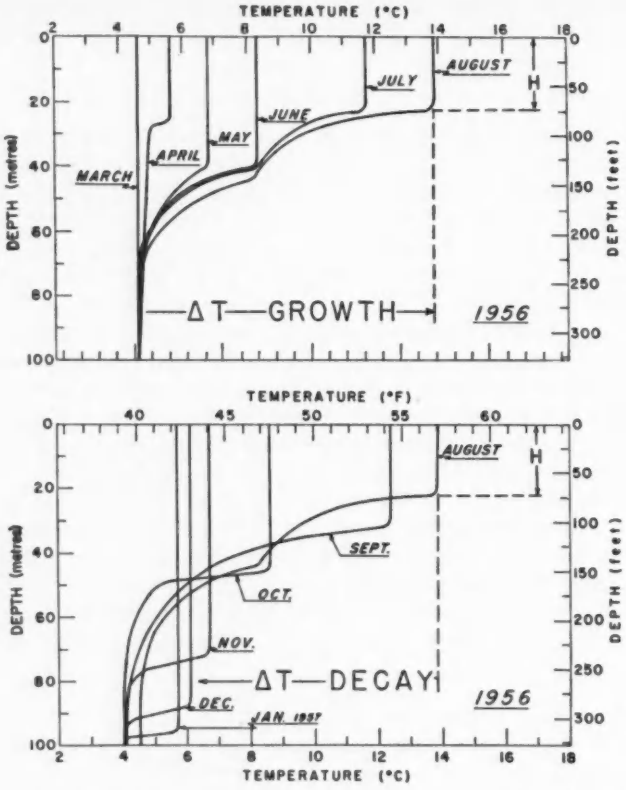

FIG. 15. Representative monthly temperature structures illustrating the growth and decay of the thermocline at Ocean Station "P".

Approximate mean monthly total hours of insolation for this coastal region, adapted from the National Research Council of Canada Climatological Atlas of Canada (1953), are shown in Fig. 16. The maximum is in July and the minimum is in the period November to January, inclusive. The coastal seawater temperatures shown in the lower diagram coincide closely with this insolation cycle.

C. Wind (Mixing)

The depth to which wind may influence the downward mixing of a property (e.g. heat) has been extensively investigated (e.g. Sverdrup *et al.*, 1942). Specifically, this depth depends on the velocity of the wind and the density structure of the water.

D. Wind (Transport, Convergence and Divergence)

Ekman (1905) found that the surface wind current was directed 45° to the right of the wind direction in the Northern Hemisphere. With a coast to the

left of an observer, and a wind directed parallel to the coast in the direction faced by the observer, Ekman showed that the surface waters will tend to move seaward from the coast, to be replaced by deeper, more dense waters from below. This is divergence, and when the deep waters are conveyed to the surface it is termed "upwelling" (Sverdrup *et al.*, 1942, p. 501). If the wind is in the opposite direction, surface water will tend to accumulate near the shore and may be depressed downward. This phenomenon is known as convergence. Classical examples of upwelling are found along the California coast in summer (Sverdrup, 1938); and of convergence in the Davidson Current, which flows northward along the same coast in winter, due to the accumulation of wind-driven surface waters (Sverdrup *et al.*, 1942, p. 725). Similar conditions of upwelling and convergence were observed near the northern end of Vancouver Island by Barber (1957), and local upwelling in the approaches to Juan de Fuca Strait was observed by Tully (1942).

Yoshida (1955) has shown that long-term variations of upwelling lag about one month after prevailing winds. Individual, short-term variations may follow the wind changes within a few days.

Winds recorded at Estevan Point are shown in Fig. 17. In this representation, all total monthly miles of wind for each direction are resolved into the two principal quadrants, northwest and southeast (i.e. parallel to the coast). The same Figure also shows the annual variation of the net value of these two components.

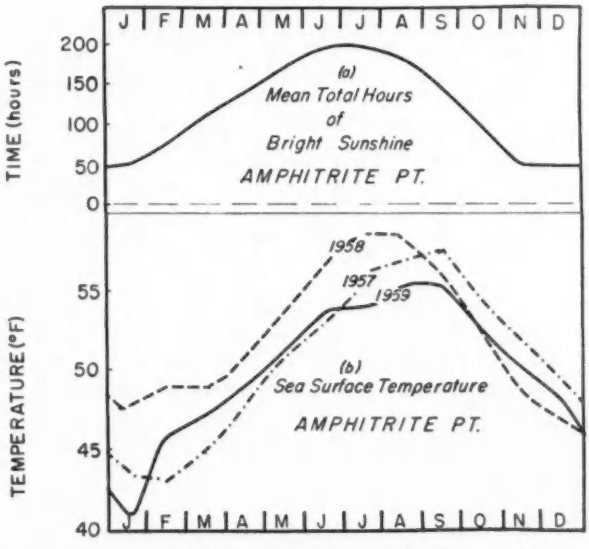

FIG. 16. (a) Mean total hours of bright sunshine per month in the vicinity of Amphitrite Point, B.C., (data to 1950); (b) Monthly mean surface temperatures recorded at Amphitrite Point (1957–1959).

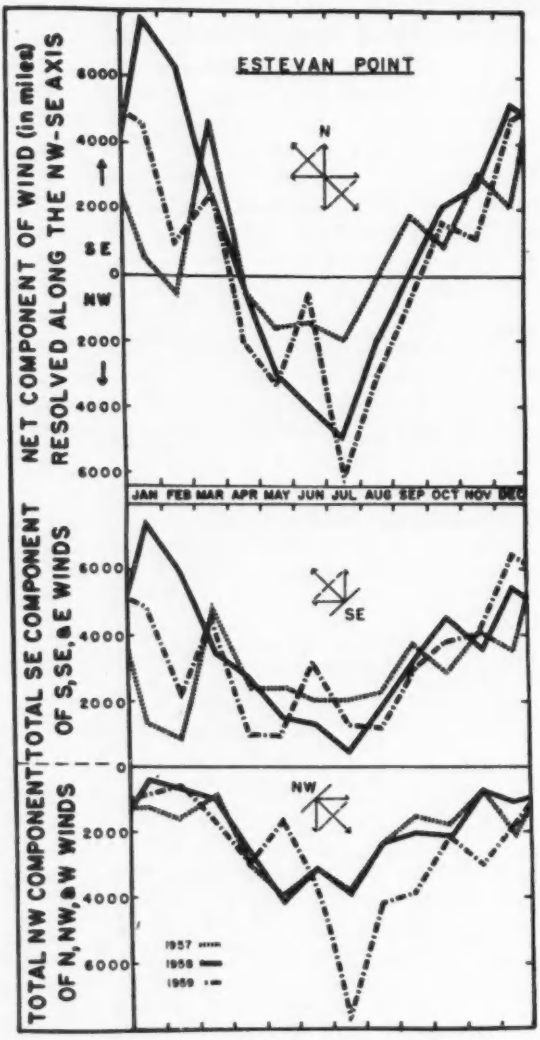

FIG. 17. Mean values, miles of wind per month recorded at Estevan Point, B.C., (1957–1959).

The wind distribution on the west coast of Vancouver Island is consequent on the mean sea-level pressure pattern (Haurwitz and Austin, 1944). The winter Aleutian Low and the summer Pacific High dominate the barometric pressure pattern and produce the winter southeasterly winds and summer northwesterlies. The unsettled spring and autumn pressure distributions produce alternating

periods of southeasterly and northwesterly winds. Such a sequence is shown for the spring of 1959 in Fig. 18. This may prove significant here, for as Sverdrup (1938) stated in his discussion of upwelling along the California coast, "a change in the wind velocity or direction which leads to a change in the transport of the surface waters may alter conditions to such an extent that large eddies develop on the boundary between the upwelled water and the offshore water". Hence considerable eddy formation may be anticipated in this region.

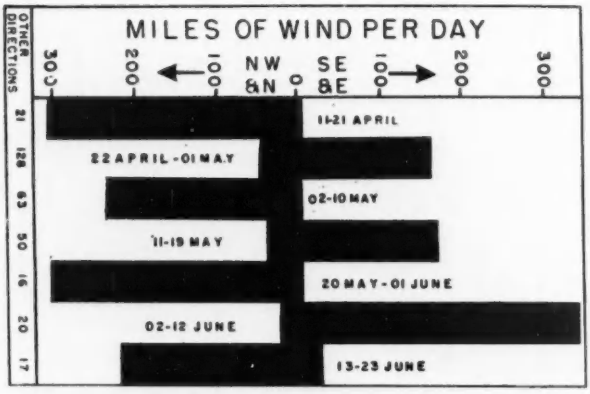

FIG. 18. Examples of alternating periods of wind direction (April–June 1959) at Estevan Point, B.C., (Fig. 2).

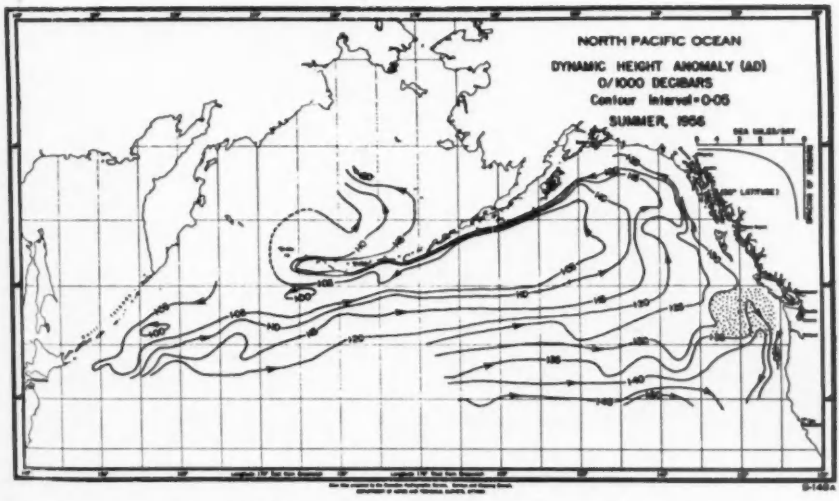

FIG. 19. Chart of dynamic height anomaly illustrating surface geostrophic flow in the North Pacific Ocean, summer 1956. Strippled area shows the eastern division of the West Wind Drift.

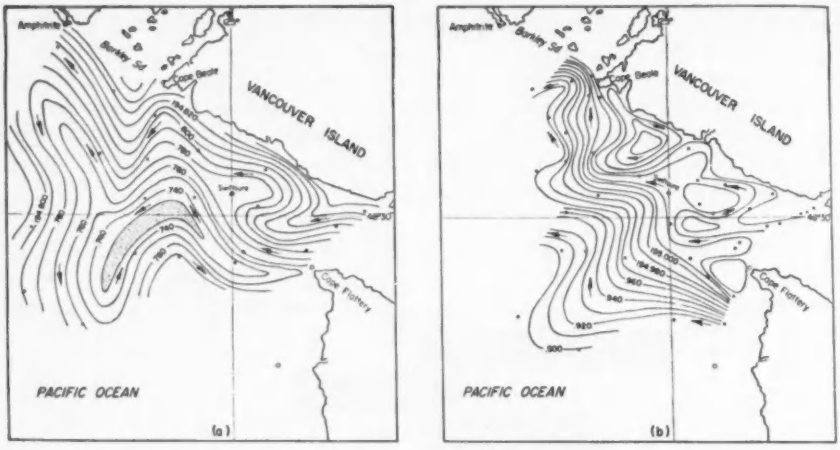

FIG. 20. Calculated surface stream lines (pressure contours of dynamic metres for a base at 200 m depth) in the approaches to Juan de Fuca Strait in 1937 (Tully,1941): (a) in late summer, an area of upwelling is shown by strippling; (b) in winter.

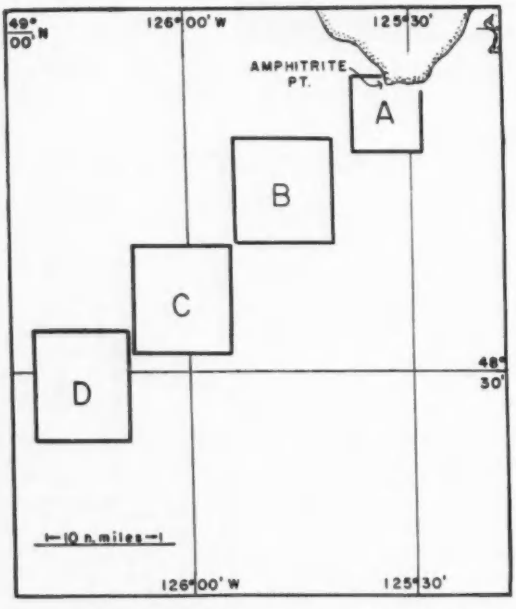

FIG. 21. Areas (A, along slope; B, continental shelf; C, continental slope; D, oceanic) into which the bulk of the data gathered seaward of Amphitrite Point on the continental shelf has been allotted.

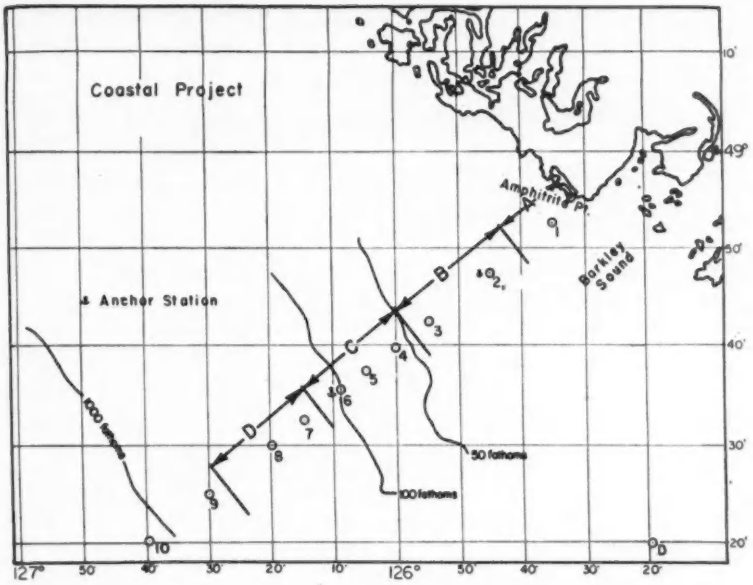

FIG. 22. Station positions of the 1960–61 coastal project, showing Areas A, B, C, D and representative depth contours.

E. TIDAL CURRENTS

A partially enclosed body of water such as an estuary will experience a reversing tidal force, while an exposed location as in the coastal region will be subject to a rotating tide. A current observed in the sea or in an estuary is the vector sum of a tidal current and a "residual" current. It is assumed that there is no net movement from the tidal current, hence the net transport is due to the residual current (Doodson and Warburg, 1941).

In this coastal region the tide is rotary (Marmer, 1926). Studies of the pattern of residual currents and of the variability of properties due to horizontal water movement require a detailed knowledge of the tidal rotation. Usually this is obtained by lengthy continuous current observations.

F. OCEAN CURRENTS

Figure 19 shows the calculated surface currents in the Subarctic Pacific Ocean. The West Wind Drift, which extends across the ocean, divides at the North American continent. A portion moves northward around the Alaska Gyre, and the remainder moves southward along the coast of the United States. The area of separation (stippled in Fig. 19) is of considerable importance to this study because it shifts from time to time and may occur to the north or to the south of this region of interest.

Drift bottle experiments (Thompson and Van Cleve, 1936) suggested that the area of division varied seasonally with the wind distribution. In August

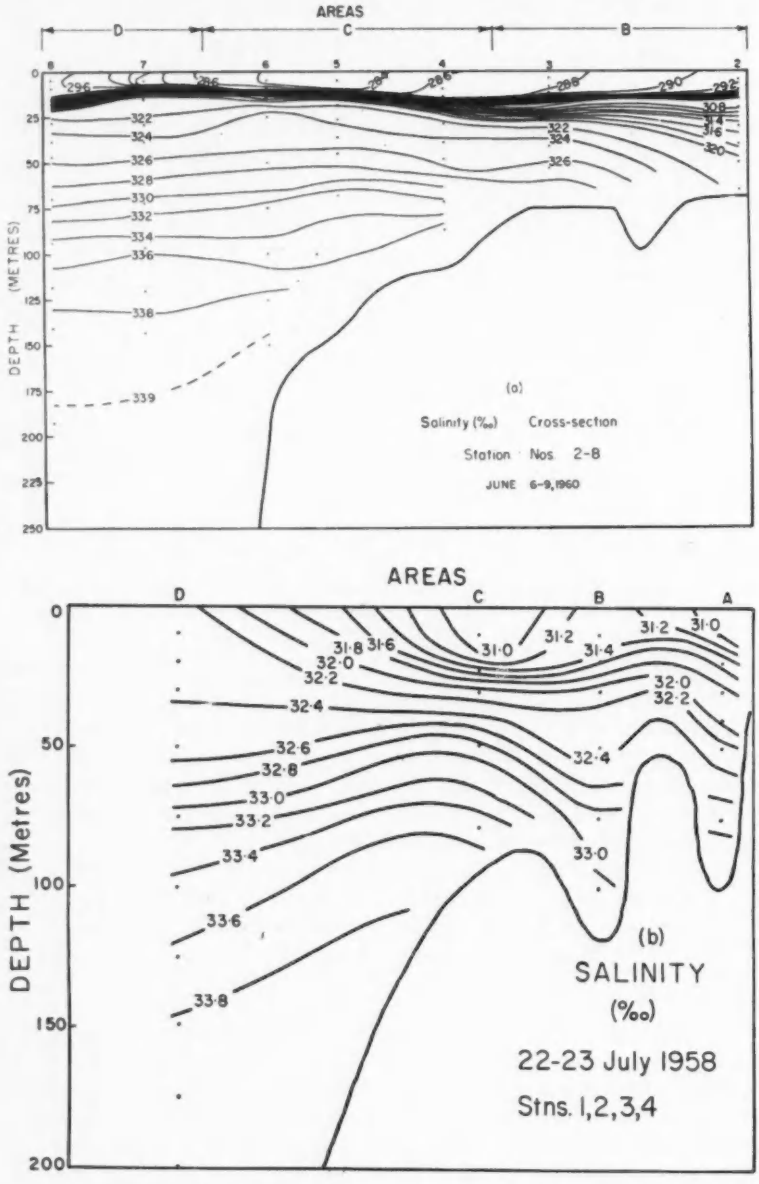

FIG. 23. Salinity structures in sections: (a) showing estuarine type with a shallow intense halocline; (b) showing a pool structure over the continental slope (cf. Fig. 21).

1931 it was observed at 50°N. In March 1932 it was found to be at least as far south as 47°N, and probably was farther south. More recently this division has been observed (Doe, 1955; Bennett, 1959; Dodimead, MS, 1958) in various positions but no definite pattern has been outlined. The region in the vicinity of the division was found to contain weak eddies.

Tully (1942) related the pattern of surface non-tidal currents at the entrance to Juan de Fuca Strait to the drainage-induced (estuarine) outflow from the strait and the seasonal wind pattern. He found that the strong summer outflow (Fig. 20(a)) first turned northward (to the right) along the coast; then, being opposed by the northwest wind, was turned southward, to form an offshore counter-current. The eddy patterned by this motion formed around a region of upwelled water (stippled in Fig. 20(a)) which was a dominant feature just northwest of Cape Flattery. The weaker winter outflow (Fig. 20(b)) showed no upwelling and was assisted by the southeast wind.

IV. APPRAISAL OF OCEANOGRAPHIC DATA

Since 1957, an effort has been made to concentrate sampling in two areas seaward of the Queen Charlotte Islands and two areas seaward of Vancouver Island. The northernmost region has a very narrow continental shelf (Fig. 1) and small drainage. Consequently, oceanic processes always dominate the oceanography. The most characteristic "coastal" region is to be found seaward of the southern portion of Vancouver Island. Most of the data available have been gathered seaward of Amphitrite Point. Analysis of these data revealed marked variability, but they also revealed that each part of the region — along the shore (A), continental shelf (B), continental slope (C), and deep ocean (D) — were distinct.

The accumulated data (1955–1960) from the region seaward of Amphitrite Point have been divided into four groups, representing the four areas (A, B, C, D) shown in Fig. 21. Subsequently, this same section has been repeatedly observed through 1960 (Fig. 22) for a more specific study of coastal processes. Some of the data from this later coastal project are also used in this discussion.

A. The Local Analysis (Salinity)

When the seaward flow in an estuary enters the open sea, it loses its identity and becomes a component of the conglomeration of other runoff contributions in a dilute coastal upper zone. Each outflow tends to the right, along the coast, in these latitudes (Rossby, 1937; Tully, 1952). In Alberni Inlet and Juan de Fuca Strait tidal action appears to create periodic discontinuities in the outflow by alternately assisting and opposing it (see later — isolated pools of fresh water). Such a mechanism ejects pools of low salinity water into the coastal region and may prove to be similar to the expulsion of isolated bodies of brackish water from Ipswich Bay, as discussed by Ford (1947). The area of study is then presented with a possibly discontinuous source of low-salinity water from Barkley Sound and Juan de Fuca Strait having a summer maximum of discharge (Fig. 13) and the local winter maximum from runoff and precipitation.

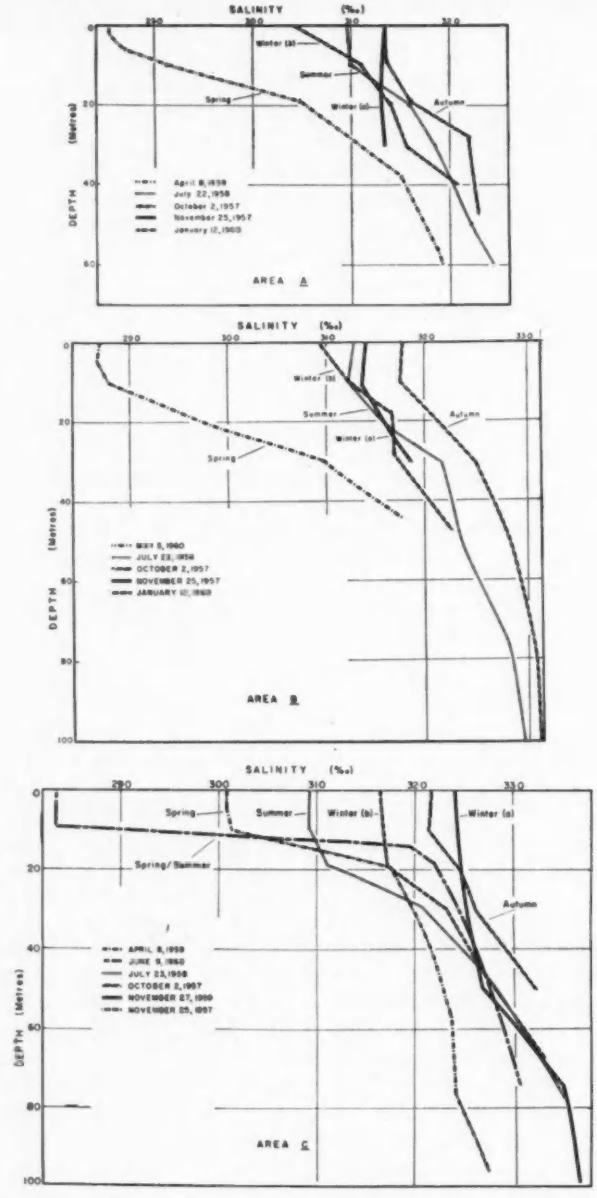

FIG. 24. Examples of salinity structure observed in Areas A, B, and C (Fig. 21).

Structure

Summer: In the months of greatest insolation (Fig. 16) a summer thermocline coincides with an intense halocline which limits the depth of upper-zone mixing. This is similar to the coincidence of the summer thermocline and a small secondary halocline in the oceanic upper zone noted by Dodimead (1961). However, the shallow coastal halocline may be identified as a seaward extension of the estuary structure (Fig. 23(a)), or as the gradient associated with isolated pools or clouds of brackish water at the surface (Fig. 23(b)). Winds during this season are usually strong enough to create a shallow isohaline layer.

Large variations of structure have been observed during summer months. Figure 24 shows representative salinity structures, including the extremes of the data collected from 1957 through 1960 in Areas A, B, and C. In May 1960, 20 consecutive observations at 2-hourly intervals were taken in Area A. Above 20 m depth, the salinity data (Fig. 25) show half the total range observed there through 4 years (Fig. 24). Below 20 m depth, the range of values observed during this 38 hours was equal to $\frac{2}{3}$ of the long-term range. A more meaningful comparison might be made with the annual range ($\triangle S$) of the grand mean monthly values of daily surface salinity observed at Amphitrite Point ($\triangle S = 2.5‰$) and

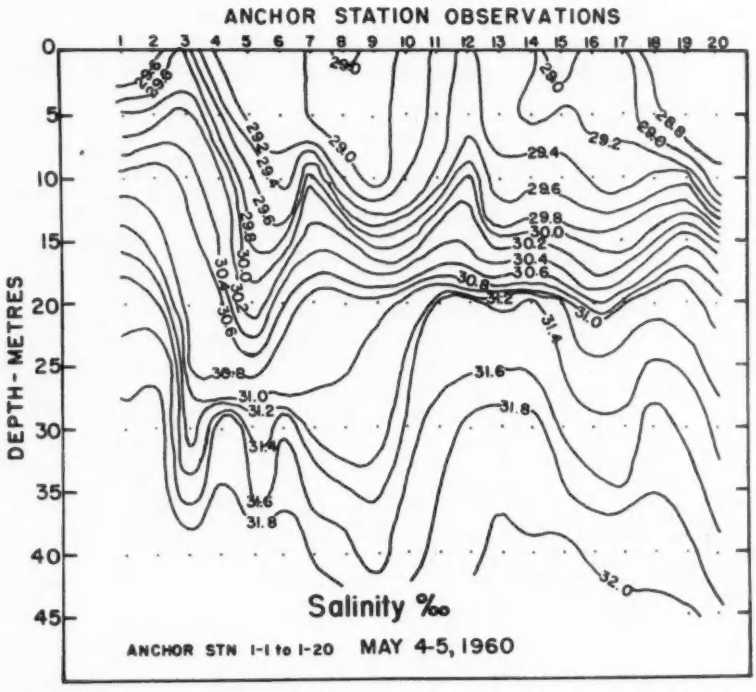

Fig. 25. A representation of salinity structure taken from 20 consecutive 2-hourly observations (May 1960) in Area A (Fig. 21).

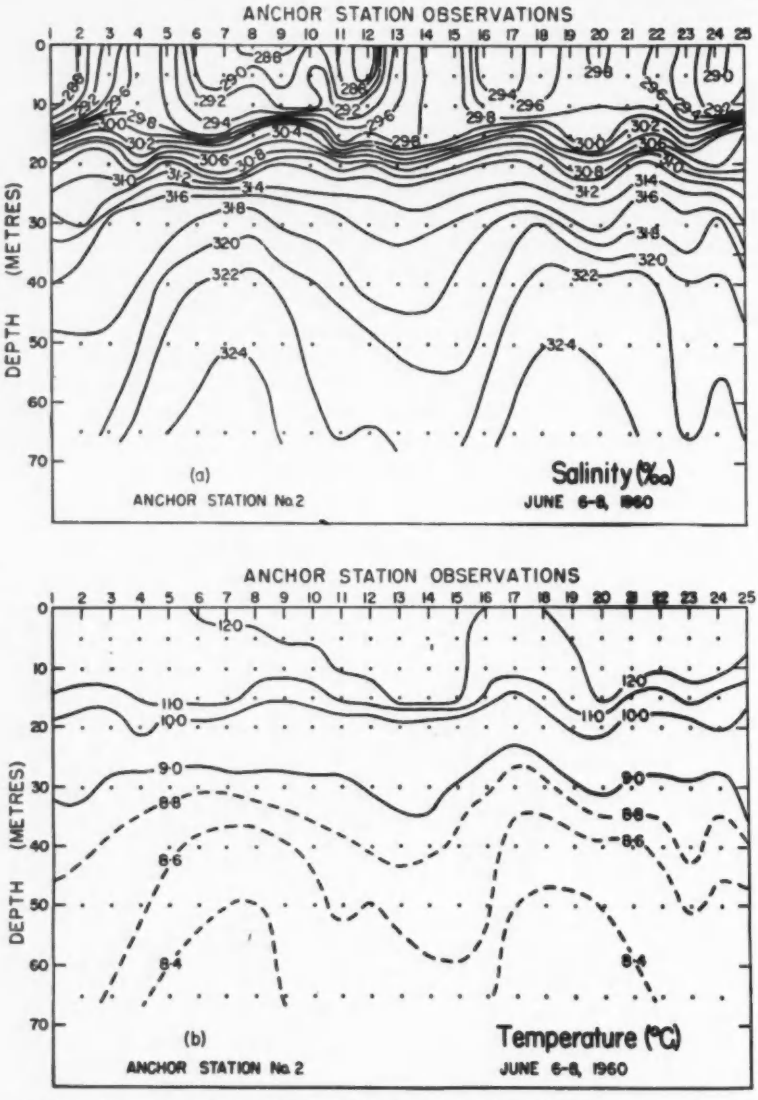

FIG. 26. Representations of salinity and temperature data taken from 25 consecutive 2-hourly observations (June 1960) in Area B (Fig. 21).

the range of surface values in the 38 hours of continuous sampling ($\Delta S = 1.2‰$). This degree of local variation clearly indicates that individual observations can offer only a generally representative structure. This does not mean that seasonal characteristics are non-existent. It confirms the conclusion from Fig. 8 that the

seasonal cycles are complicated by short-term ambient variations. These are probably due to horizontal discontinuities passing the point of observation. Such discontinuities may be caused by the intermittent discharge from Juan de Fuca Strait (pools of brackish water).

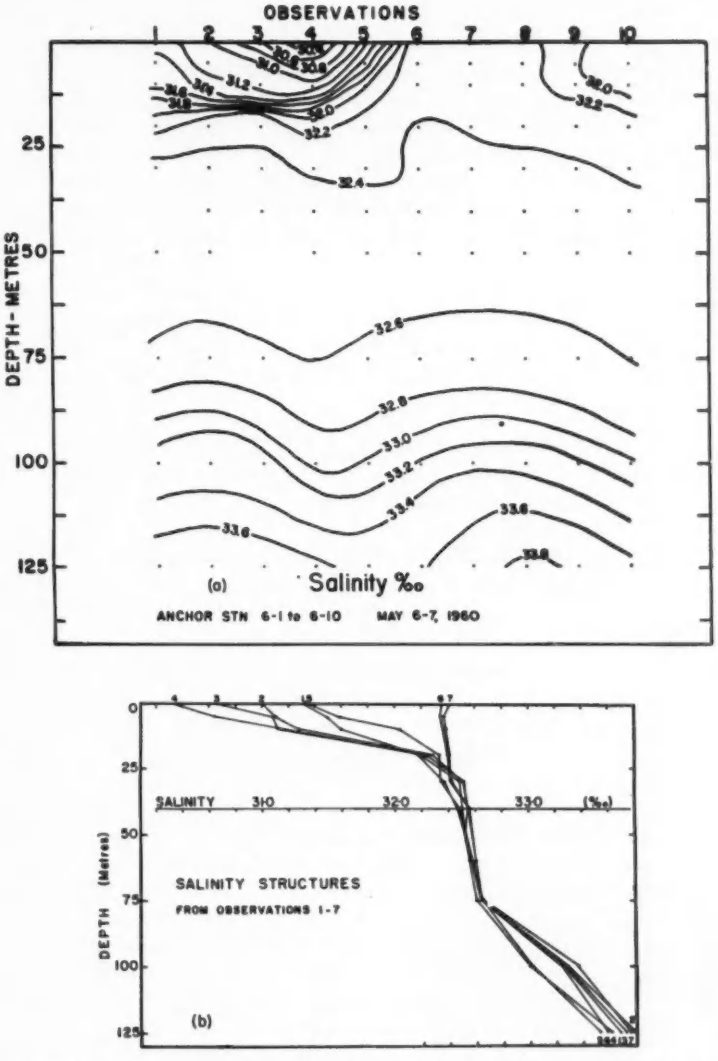

FIG. 27. (a) A representation of salinity data taken from 10 consecutive 2-hourly observations midway between Areas C and D (Fig. 21). (b) Salinity–depth structures of data from observations 1–7 showing the effect of the low-salinity pool.

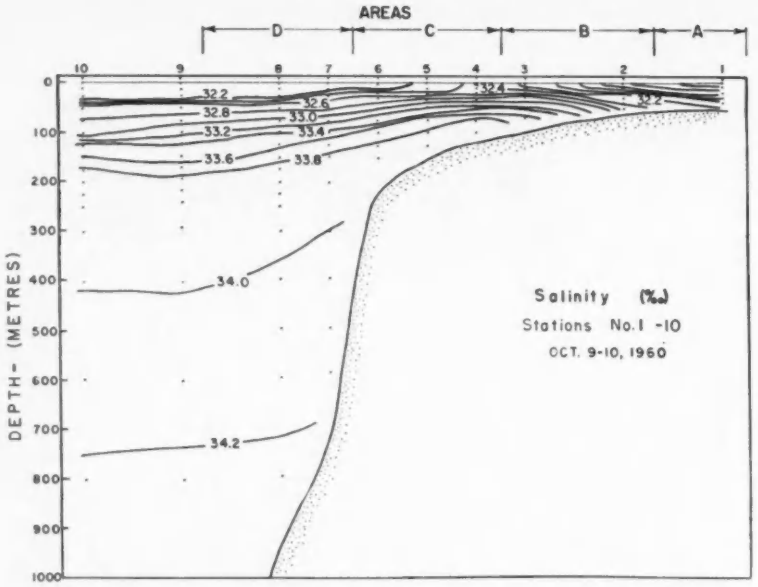

FIG. 28. Salinity structure in a cross-section (October 1960) showing the upward slope of isohalines toward the continental shelf (cf. Fig. 22).

A similar degree of variability was found to exist further seaward over the shelf. This is evident from a comparison of the range of variation of total salinity data at Area B (Fig. 24) with that of 25 consecutive observations taken in June 1960 (Fig. 26). Also, at a location between Areas C and D (Sta. 6, May 1960; Sta. 6, June 1960), a series of observations indicated extensive changes in the upper 20 m of depth. The May picture (Fig. 27(a)) shows a period of low surface salinity, which may be attributed to the passage of a pool of brackish water. Figure 27(b) shows the sequence of structures during its passage. Observations 4 and 6 show that the marked halocline ($\Delta S = 1.84‰$) in the upper 20 m depth gave way to an almost completely isohaline structure in 4 hours.

Below the shallow coastal halocline (Fig. 23), a less intense deep halocline is evident over the shelf region. Judging by the salinity values this is associated with the ocean halocline and has a salinity difference of about 1‰ between its top and the sea bottom, in those parts where the oceanic lower zone does not appear. Isohalines from the upper zone of the ocean structure slope downward and those from the ocean halocline slope upward to form this gradient. It appears that the isohalines sloping upward to the shelf develop during the summer (July) rather than in the spring (June). This structure suggests a divergence. Figure 28 shows a more advanced configuration in October 1960.

It appears from these observations that the deep halocline rises toward the shallow halocline. In this area, the deep isohalines have not been observed to

rise to the surface, as in the classical sense of upwelling (Sverdrup *et al.*, 1942, p. 501). Furthermore, the depth of the shallow coastal upper zone and halocline are disturbed little, if any, in many observed cases. Here, the rise of isohalines from the oceanic halocline shoreward into the zone below the shallow (estuarine) halocline may be the result of mixing into what originally was an oceanic upper zone, that now has been separated from surface mixing forces by the overlying shallow halocline.

An example is shown in Fig. 23(a), where the shallow halocline extends well offshore. There is a complete lack of an oceanic upper zone, even at Sta. 8 well beyond the continental slope. Figure 23(b) shows the shoreward rise of the 32.6 to 33.8‰ isohalines to the shallow coastal halocline at Sta. C. The structure observed later in the season (Fig. 28) more closely approaches the divergence concept. It appears to be associated with the prevailing wind direction (as discussed in Section III.D). Station 4 in this example appears to be in an area of divergence.

Typical oceanic salinity structures were observed in Area D, over the continental slope. Figure 29 shows some examples, and Table I shows the depths and salinities of the more important structural limits. The features of the upper zone in summer have a degree of variation similar to that observed in the other

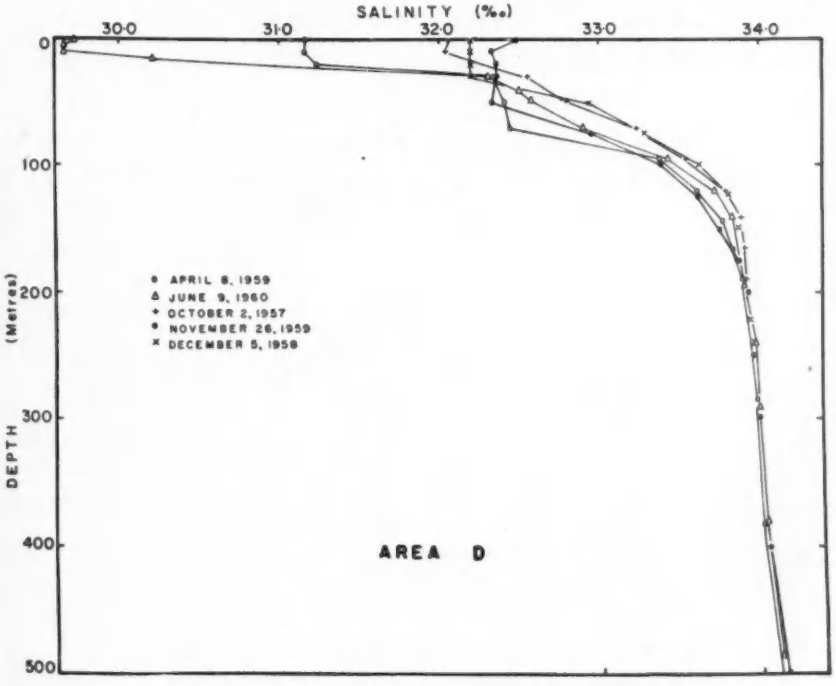

FIG. 29. Examples of salinity structure in Area D (Fig. 21).

coastal areas (A, B, C). The lowest surface salinities were found in June (Table I). The upper and lower boundaries of the oceanic halocline show no definite seasonal variation in either salinity or depth. The values at the lower limit are all 33.8± 0.13‰. Below this halocline, there was very little variation in salinity at any level. This is consistent with the conclusions of Dodimead (1961) and Tully *et al.* (1960) that the bottom of the oceanic halocline was the ultimate limit of local surface influence. It is of interest to note that at 250 m depth the range of variation of salinity was $\triangle S = 0.06‰$ (14 observations), while at 500 m depth, $\triangle S = 0.17‰$ (10 observations). Evidently, in the vicinity of the continental slope, there was a zone of minimum variability at about 250 m depth.

Winter: Cold air temperatures and a decrease in the outflow from mainland sources combine with wind mixing to reduce vertical stability, and result in homogeneity to a greater depth than in summer. In the shallow areas (A, B, and C) these winter conditions often annihilate the halocline. Generally, surface salinities in the autumn and winter are greater, and those at 50 m or deeper are less than the corresponding spring and summer values (Fig. 24). At times, however, winter runoff combines with precipitation to create a seaward salinity gradient in the near shore areas.

At Area D, the winter salinity structures corresponded essentially to those in the deep ocean. Deep mixing provided an isohaline upper zone as shown in Fig. 29. Surface salinity values generally increased, initiated by an onshore

TABLE I. Salinities and depths corresponding to oceanic structural features observed at Area D (Fig. 21).

Date	S_0	Z	U	S_u	L	S_L	S_{250}	S_{500}
	‰	m	m	‰	m	‰	‰	‰
Jan. 12, 1960	31.88	25	25	31.88	160	33.81	33.97	34.17
Feb. 27, 1961	32.47	70	70	32.45	175	33.89	33.96	34.08
Mar. 28, 1961	32.59	30	75	32.71	215	33.91	33.95	34.10
Apr. 8, 1959	32.17	10	75	32.45	160	33.84	33.97	34.09
May 6, 1960	32.37	20	75	32.77	170	33.84	33.97	34.14
May 14, 1957	32.33	10	75	32.72	120	33.74	33.94	–
June 9, 1960	29.72	15	15	30.21	120	33.79	33.98	34.12
June 14, 1959	31.85	10	20	31.93	145	33.83	33.96	34.14
June 16, 1960	30.80	10	10	30.76	135	33.83	33.99	–
July 12, 1957	31.90	0	50	32.62	160	33.82	33.94	–
Oct. 2, 1957	32.07	10	10	32.05	125	33.87	–	–
Oct. 8, 1960	32.13	25	25	32.13	195	33.93	33.96	34.07
Nov. 25, 1957	32.35	30	30	32.34	120	33.68	33.96	–
Nov. 27, 1959	32.39	50	50	32.36	180	33.92	33.95	34.00
Dec. 1, 1960	32.39	50	50	32.36	138	33.69	33.93	34.06
Dec. 5, 1958	33.21	30	30	33.21	130	33.86	–	–

S_0 = salinity at surface;
Z = depth of the oceanic isohaline upper zone;
U = depth of upper boundary of the oceanic halocline;
S_u = salinity at U;
L = depth of lower boundary of the oceanic halocline;
S_L = salinity at L;
S_{250} = salinity at 250 m depth;
S_{500} = salinity at 500 m depth.

movement of higher-salinity surface oceanic water. Upper-zone salinity inversions were not uncommon and suggest an instability. The fact that isohalines from offshore waters generally bent down towards the shelf and slope regions in winter (Fig. 30) confirmed an alongshore convergence, hence the presence of onshore movement which forms a stream northward along the coast (Barber, 1957).

Distribution

Figure 31 shows the average of mean monthly surface salinity values, for the years indicated, at Amphitrite Point, Swiftsure Bank Lightship, Umatilla Reef Lightship, and Race Rocks Lightstation. The curve for Amphitrite Point indicated maximum salinities from May through July and a period of minima from December through January. Pickard and McLeod (1953) attributed this cycle to an alternation of wind-induced summer upwelling and heavy winter precipitation. This sequence also satisfies the concept of seaward dissipation of coastal water by divergence in summer, and the conservation of estuarine discharge along the coast by convergence in the winter.

Seaward over the shelf region, it appears that the lowest surface salinity values may be found in spring and summer (Table I and Fig. 24). Runoff from mainland sources is at its peak in the summer months and is reflected in the June–August Race Rocks salinity data (Fig. 31). However, the coastal low

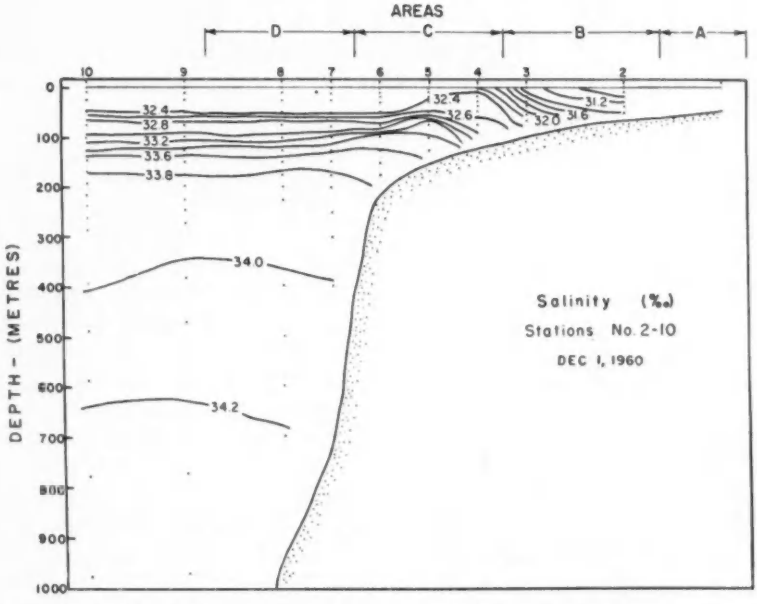

Fig. 30. Salinity structure in a section normal to the coast (Fig. 22) observed in December 1960 showing the downward slope of isohalines toward the continental shelf.

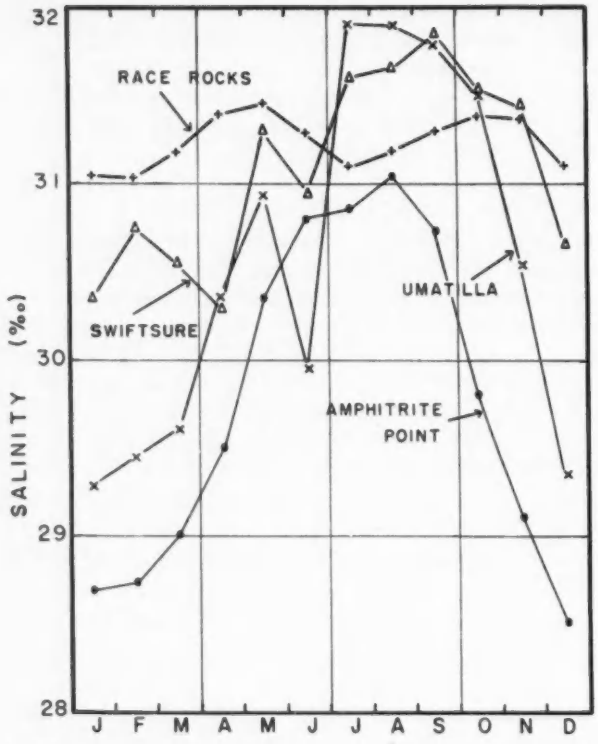

FIG. 31. Averages of mean monthly surface salinity values observed at Race Rocks (1942–1959) and Amphitrite Point (1935–1959) lightstations, and at Umatilla Reef (1956–1959) and Swiftsure Bank (1955–1959) lightships (locations in Fig. 2).

salinities at Amphitrite in April–June appear to precede this runoff and may be attributed to Vancouver Island runoff (where the mountains are lower than on the mainland and the snow melt is earlier) and the change in the wind to a predominately northwesterly pattern. This causes the winter accumulation of runoff and precipitation-diluted waters to spread seaward over the shelf and create the initial spring salinity structure (Fig. 32(a)). The diminishing dilution through late summer is retained in the upper zone by the stability of the summer thermocline.

Summer runoff through Juan de Fuca Strait and/or from the Columbia River is not generally apparent in surface salinity data from Swiftsure and Umatilla, despite occasional extremely dilute values in the summer data. The behaviour of the salinity pattern at Swiftsure during late summer may be related to Tully's (1942) description of the summer upwelling (divergence) area formed in that region by the outflow from Juan de Fuca strait (Fig. 20(a)). In a time of

predominantly northwest winds, the stream from Juan de Fuca Strait enters the ocean from the north side of the strait (due to Coriolis force) and is directed seaward, then southward by the opposing winds. The cyclonic eddy thus formed becomes an area of upwelling and hence of high salinity. Such might produce complex salinity distributions in the coastal region by meandering or breaking into segments.

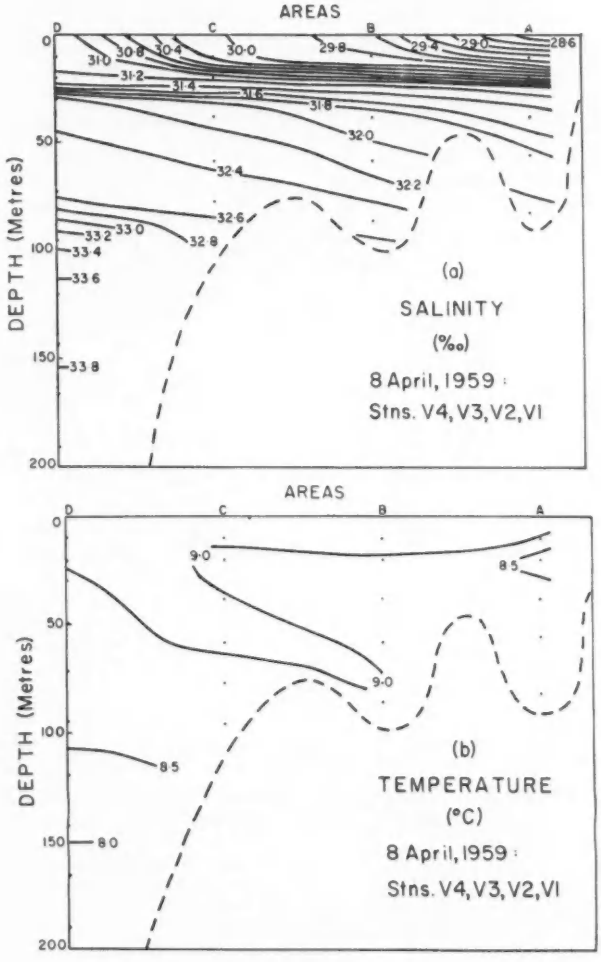

FIG. 32. Salinity and temperature structures in cross-sections seaward from Amphitrite Point (Fig. 21) in April 1959 showing the occurrence of the salinity structure and the lack of development of any temperature structure.

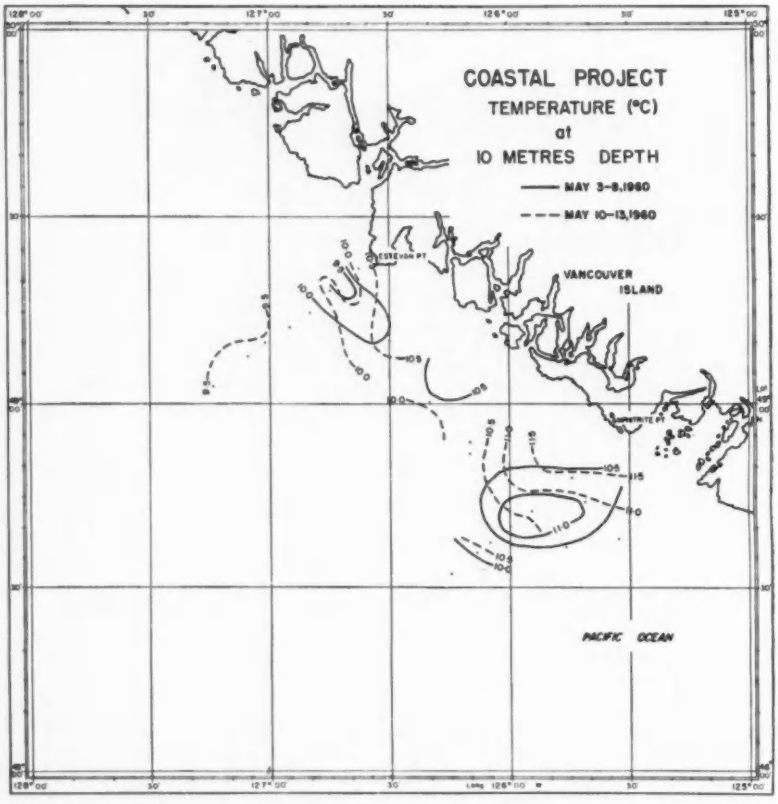

FIG. 33 (Part I). Horizontal distribution of temperature along the west coast of Vancouver Island at 10 m depth during May 1960.

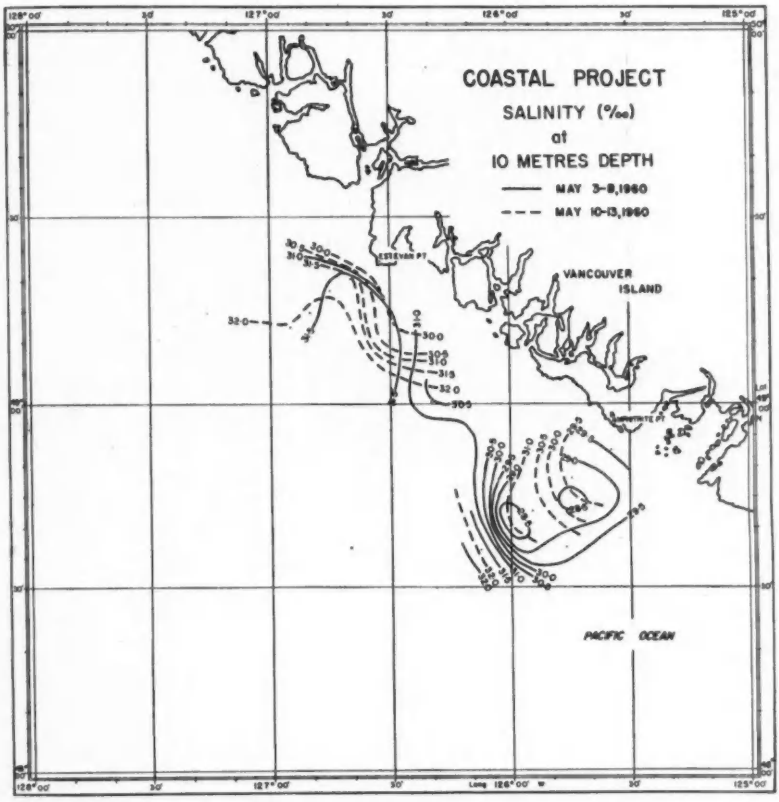

FIG. 33 (Part II). Horizontal distribution of salinity along the west coast of Vancouver Island at 10 m depth during May 1960.

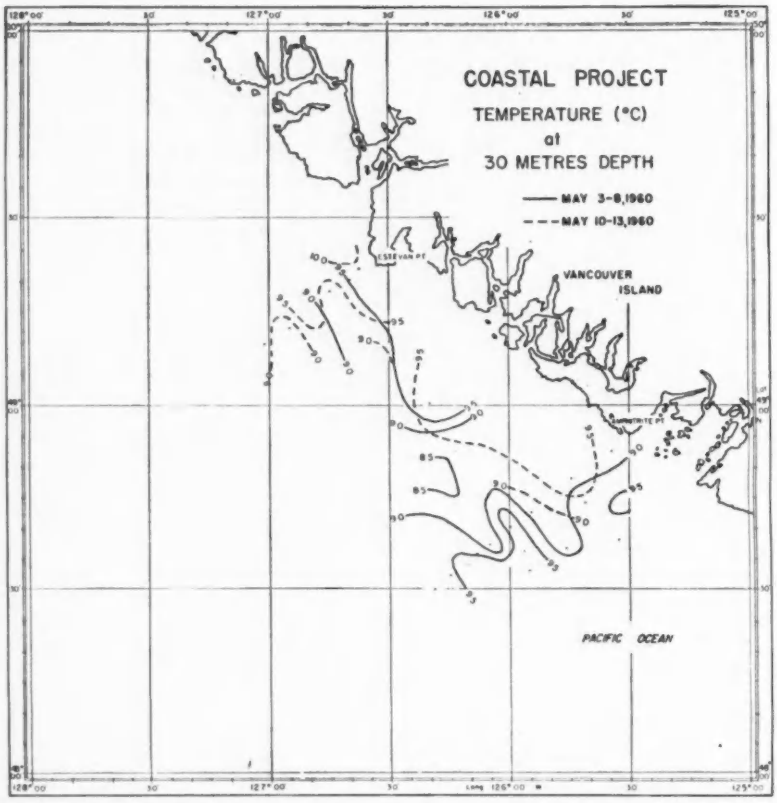

FIG. 33 (Part III). Horizontal distribution of temperature along the west coast of Vancouver Island at 30 m depth during May 1960.

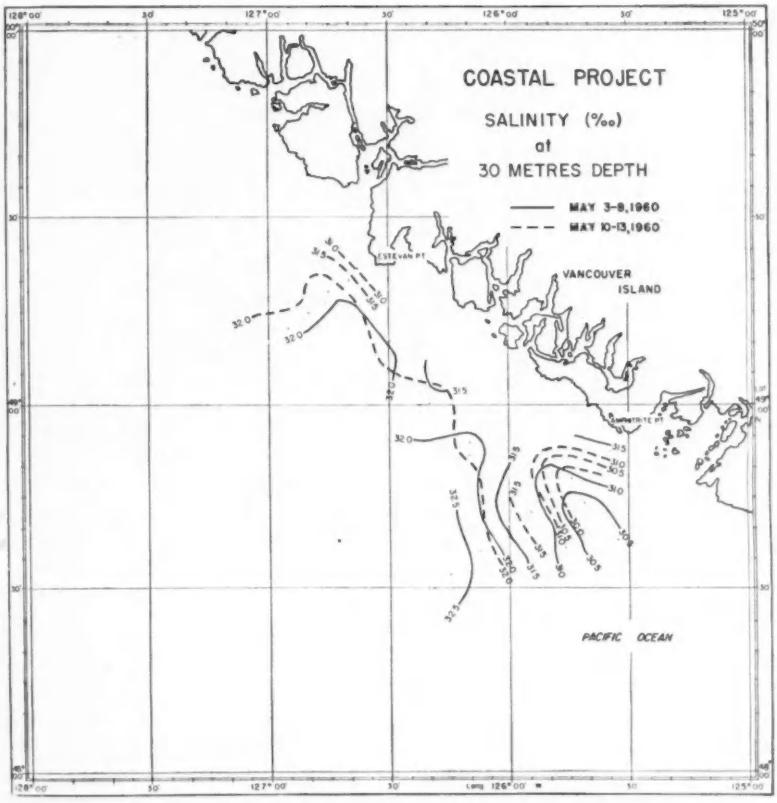

FIG. 33 (Part IV). Horizontal distribution of salinity along the west coast of Vancouver Island at 30 m depth during May 1960.

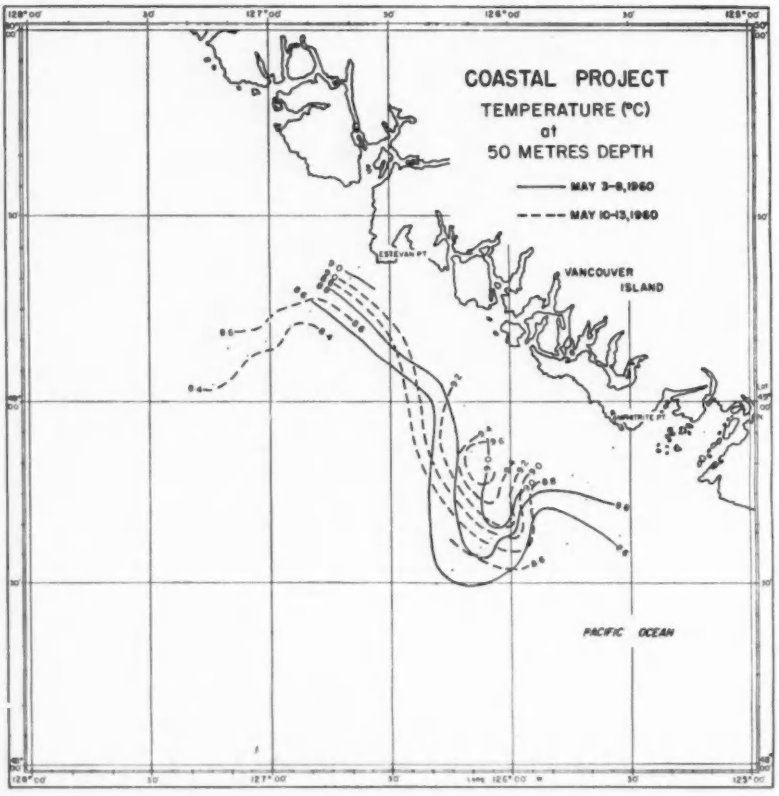

FIG. 33 (Part V). Horizontal distribution of temperature along the west coast of Vancouver Island at 50 m depth during May 1960.

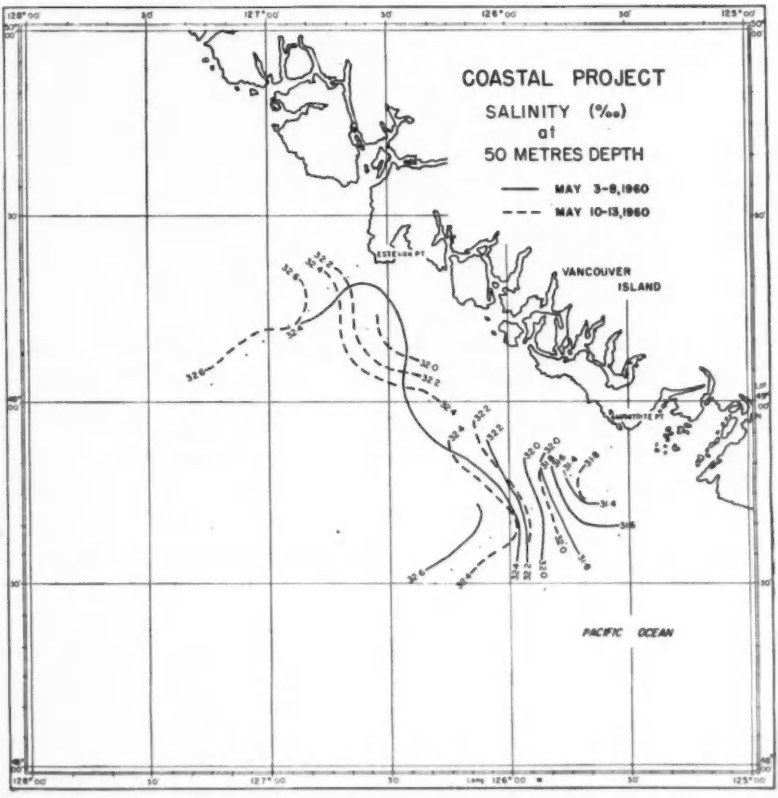

FIG. 33 (Part VI). Horizontal distribution of salinity along the west coast of Vancouver Island at 50 m depth during May 1960.

By analogy with the Juan de Fuca discharge, it may be reasoned that Columbia River runoff in summer would be directed southward off the coast. The winter–summer patterns in this case are not yet clear. High surface salinities during the summer at Umatilla Reef suggest an upwelling comparable to that at Swiftsure.

The horizontal salinity distribution in the area (A, B, C, D) appears to be dominated by eddies in the spring and summer. These probably result from the mechanics of discharge from Barkley Sound and Juan de Fuca Strait, and from the wind.

It has been found that the general distributions (Fig. 3) indicate decreasing surface salinities from mid-ocean shoreward in all seasons. Parts I–VI of Fig. 33 show the salinity and temperature distributions observed at 10, 30, and 50 m depths during the first and again during the second week in May 1960. The trend of decreasing salinities shoreward is evident. Superimposed on these trends there were irregularities of distribution, indicative of pools, which changed markedly during the week from one survey to the next. These data confirm the conclusions drawn earlier (Section II) from the consideration of more widely spaced observations.

Autumn and winter distributions, determined to a larger extent by greater wind mixing, are presumably simpler in detail than summer distributions.

B. The Local Analysis (Temperature)

Summer: The annual variation of sea surface temperature (1957–1959) at Amphitrite Point is shown in Fig. 16. Figure 34 shows surface and near-bottom temperatures observed in Areas A, B, C, D from all available data. The seasonal cycle is apparent in the surface data. Figure 35 shows the temperatures at 100 m depth in Area D, and Area F (just over the slope, seaward of Cape Cook north of Area D).

In spring and summer, waters are subject to maximum insolation. Below a shallow (10 to 20 m depth) wind-mixed isothermal layer, there exists an intense thermocline (Fig. 36, June structure). This thermocline was found to extend to a depth of at least 30 m and occasionally to the bottom in shallow regions. The variation in depth of the "near bottom" observations prevents a discussion of the annual variation of bottom temperature from their values. However, comparatively low values are usually evident in the summer period. In Hecate Strait, Barber (1957) found lower bottom temperatures in summer than in winter. A comparison of Fig. 6 (July) and 37(b,c) (January and February) suggests a similar occurrence in the coastal region. As shown in Fig. 35, this seasonal cycle has been observed at 100 m depth seaward of the continental shelf.

Short-time variations in the temperature structure have been observed and appear to be associated, to some degree, with salinity variations. Figures 26(a) and (b) show an example of coincident salinity and temperature variations during 48 hours of observation in Area B (Fig. 21).

It has been noted that the surface horizontal temperature distribution in summer shows decreasing values shoreward in the upper zone (Doe, 1955; Barber,

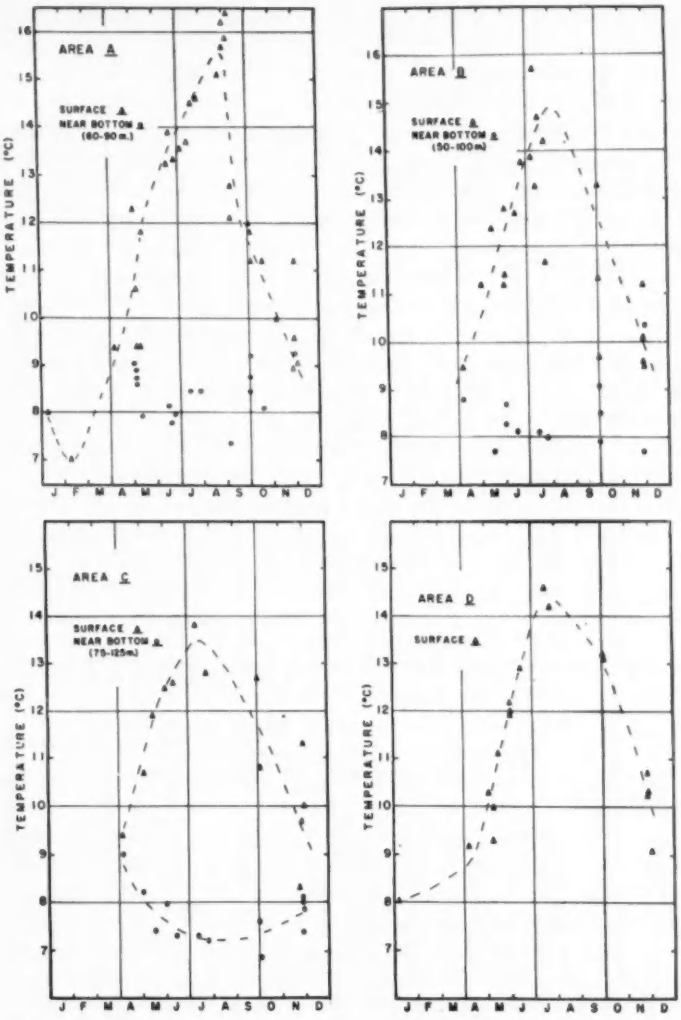

FIG. 34. Surface and near-bottom (various depths) temperature values recorded in Areas A, B, C, D (Fig. 21) (over a period of years). Dashed lines are for a guide only.

1957; Bennett, 1959). In May 1960 it was found that temperatures increased shoreward but that the pattern was greatly distorted by pools or eddies (Fig. 33). The gradient observed in July 1957 was opposite to that observed in July 1958 (Fig. 6). If a definite consistently negative gradient were to be established from sea to shore over the shelf, it seemingly must occur in the latter part of summer

and may indicate a seasonal upwelling, or wind-driven seaward transport of surface waters which become warmed en route. Previous references to this effect of upwelling in this area have been made by Doe (MS, 1952, 1955); Tully and Doe (MS, 1953); and Pickard and McLeod (1953).

In Area D, the seasonal cycle of the temperature structure may be compared to that (Fig. 15) at Ocean Weather Station "P". In every season, there exists an isothermal zone down to at least 20 m depth. The underlying thermocline appears to change seasonally as a function of insolation and mixing in the same manner as at Station "P".

Winter: The winter temperature structure in waters over the continental shelf is completely altered by the decrease in insolation and the advent of strong seasonal southeasterly winds. Figure 36 shows examples of the sequence of structures from mid-summer to mid-winter. Surface temperatures decrease and the approach to vertical homogeneity is aided by the wind mixing. Completely isothermal conditions, as well as temperature inversions, have been observed. These winter temperature conditions were found to persist even while the spring salinity structure was developing strong vertical gradients (Fig. 32).

The predominant southeast winter winds generate a northwestward flow which, due to Coriolis force, conserves light surface waters along the coast. These waters, combined with the heavy seasonal runoff from Vancouver Island, produce a stream running northward along the coast. In autumn, when upper-zone waters are still warm, this results in a general increase in surface tempera-

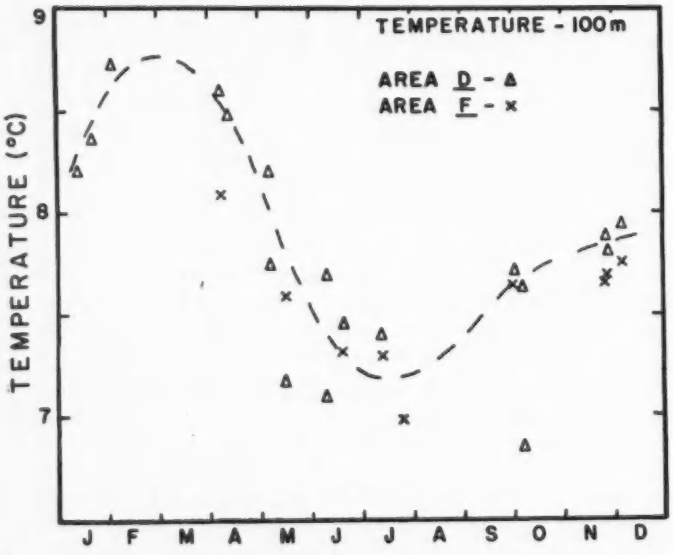

FIG. 35. Temperatures at 100 m depth at Areas D (oceanic) (Fig. 21) and F (continental shelf at north end of Vancouver Island, see text) observed from 1957 to 1960. Dashed line is for guide only.

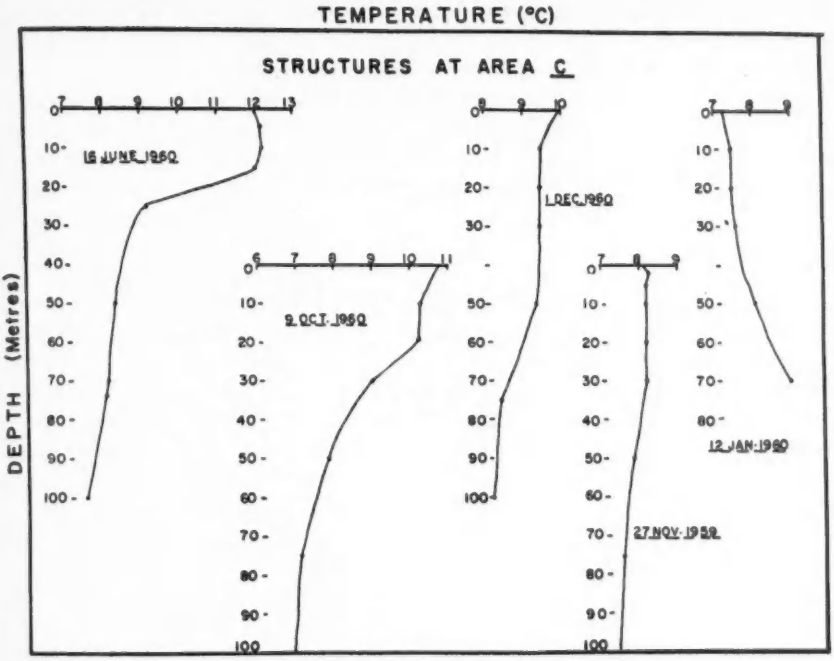

FIG. 36. Examples of temperature structure at Area C (Fig. 21), showing a spring–summer (June) type and the transition from autumn to winter types (October to January).

ture shoreward (Fig. 37(a)). However, as the season advances, and surface waters become progressively cooler, the winter onshore movement (Section III.D) results in temperatures lower next to the coast than offshore (Fig. 37(c)).

It is evident that the movement of fresh water seaward over the shelf in spring is independent of the stability of the thermocline in the development of the salinity structure. Increased insolation eventually produces the summer temperature structure in the upper levels while lower-zone temperatures decrease. This decrease is probably due to an "onto the shelf" movement of cold saline oceanic water as part of the divergence process. Mixing in the zone below the spring "estuarine" halocline in coastal waters probably accounts for the cooling at these depths early in the summer. This is coincident with the salinity mixing outlined in Section IV.A.

TEMPERATURE INVERSIONS

Temperature inversions between 100 and 200 m depth in the North Pacific Ocean have been investigated. Doe (1955) proposed that they indicate the depth of seasonal cooling and are associated with a lag in the response at depth to the surface heating. Figure 37(b) illustrates a winter temperature inversion over the continental shelf. It has been noted that isotherms slope downward

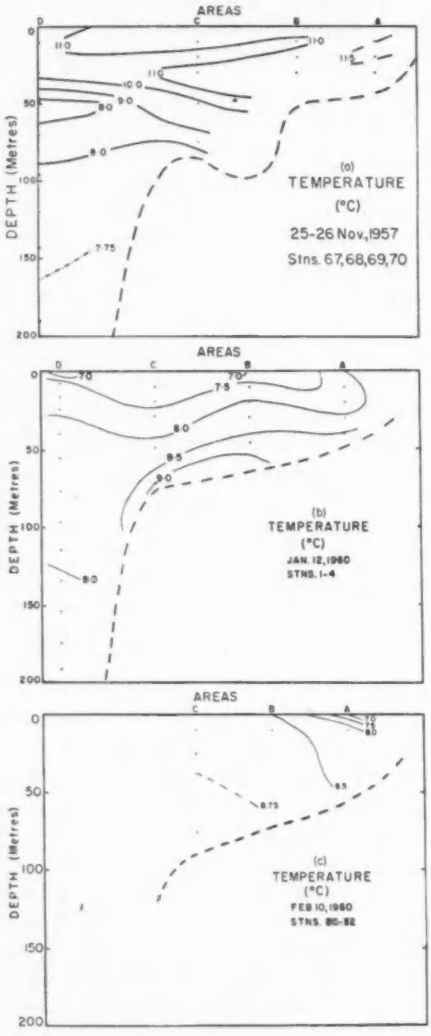

FIG. 37. (a) Temperatures in a cross-section seaward of Amphitrite Point (Fig. 21) in autumn, showing a warming shoreward and relatively warm water on the shelf. (b, c) Temperature cross-sections in the same area in winter, showing the trend to a cooling shoreward and decreased surface temperature on the shelf.

to the coast at this time. Hence it appears that while winter cooling reduces near-surface temperatures, the wind-induced circulation creates a convergence pattern which may result in a sinking of the warm water which comprised the summer thermocline. This may be regarded as a relaxation of the summer divergence process which drew the cool deep water up onto the shelf. Maximum temperatures in the winter inversion structures will then be higher than temperatures found in those depths in summer (Fig. 35).

V. CONCLUSION

From the presentation of data included in this paper, a pattern of oceanographic events has been described. The magnitude, extent, and importance of these events cannot be derived without a more sophisticated and specialized approach. It has been shown that interpretations of any set of data in the coastal region must take into account the nature and extent of the property changes which may be affecting the distributions at the time of observation. The causes and effects of this variability will mean more to a study of oceanographic processes than any statistical record of data.

At the time of writing this paper, sets of "time series" data were being acquired for the purpose of studying the influence of tide and meteorological elements on the ranges of values observed.

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The Pollett Apron Seine[1]

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ABSTRACT

A two-man block seine about 16 feet (5 m) long has been modified for studying populations of small fish in the shallow, rapid salmon streams of eastern Canada. It is usually used in conjunction with DC electrofishing aids. The special feature of this seine is an extra strip of netting, the "apron", attached closely to the foot-line but extending back about 1 foot (30 cm) to a free edge over the main netting. This free edge of the apron is held about 4 inches (10 cm) above the main netting by wire gate frames fixed to the foot-line. Fish which would otherwise escape off the net are held in the space between main netting and apron. Construction and use are described in detail.

A BLOCK SEINE of special design has facilitated study of populations of small fish living in Maritime Atlantic salmon streams. Fisheries scientists both on this continent and in Europe have expressed interest in it. Salient features of its construction and use are shown in the accompanying illustrations (Fig. 1–5).

The seine is ordinarily used in conjunction with direct current electrofishing apparatus (Smith and Elson, 1950; Elson, in press). Fishing is often in rapids and over gravel or coarser bottom. Depth of water fished seldom exceeds 3 feet (1 m). In general, fish affected by the electrical field are either "led" with the anode or swept by water flow down into the belly of the net.

When a simple seine was used many of the fish, upon being released from the electrical field, darted upstream and escaped. Usually such fish swam up close against the belly of the net. A narrow apron attached to the foot-line and hanging back over the leading edge of the main body of the seine was designed to block such escape. It does this effectively and also appears to provide an attractive form of shelter, so that most of the fish remain quietly between apron and main netting until the seine is lifted.

Making the Apron Seine

There are three basic parts to be assembled, (1) framework, including handles, foot-chain and apron gates, (2) main body of netting and (3) the apron. Measurements are given as a guide, but are not critical. Suggested metric measurements are in brackets.

(1) Framework

HANDLES. Ordinary hardwood shovel handles about 54 inches (1.5 m) long are used. An eye-bolt of quarter-inch (6.4 mm) stock is firmly riveted through a steel ferrule mounted on the lower end of each handle.

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FOOT-CHAIN. A length of welded steel chain has been found much more efficient and durable as a foot-line than rope with lead weights attached at intervals. The length of the completed seine will be almost the same as the length of chain used. Chain of $\frac{3}{16}$-inch (5 mm) stock with links having an inside length of about $\frac{7}{8}$-inch (22 mm) has sufficient weight to hold the net down in fairly swift water and is flexible enough to lie close to irregular stream bottom contours. Larger chain, besides being unnecessarily heavy to handle, tends to hold the net off the bottom enough that small fish can escape under or through the links. A chain length of 12 to 16 feet (4 to 5 m) has been found most satisfactory, the longer length being preferred in wider streams. The two end links of the chain are fastened into the eye-bolts in the handles.

APRON GATES. In order that fish may swim upstream along the belly of the net and then get under the apron, the latter must be held away from the main body of the net. Wire "gate frames" serve this function. Gate frames are made from $3\frac{1}{2}$-foot (1.1 m) lengths of stiff, 8-gauge copper wire. The wire is pushed through a piece of rubber tubing ($\frac{1}{8}$-inch (3 mm) walls and $\frac{3}{16}$-inch (5 mm) bore) so that the tubing covers the middle 9 or 10 inches (23 or 25 cm) of the wire. This tubing forms a cushion between wire and netting; without it the netting would soon be cut through where the gate frames hammer it between wire and rocks each time the net is set. Wire and tubing are then bent into a rectangular loop, using for a form a billet of wood about $2\frac{1}{2}$ by 4 inches (6 by 10 cm) in cross section. The free ends of the wire are twisted together twice in the middle of one side of the rectangle to secure the loop. They are then bent out parallel to this side of the loop and at the level of the corners of the loop bent again at right angles to the plane of the loop. The free ends of these foot-long (30 cm) arms of the gate frames are then clinched into appropriate links of the foot-chain, using about 1 inch (2.5 cm) of the wire for clinching each arm. There are three links intervening between those two into which the arms of one gate frame are fastened. These gate frames are placed every 16 inches (50 cm) across the seine starting 16 inches (50 cm) from the handles. All links to which gate frames are fastened must lie along one plane when the chain is laid out with no twist. When in position, all the loops hang down in the same direction.

(2) MAIN BODY OF SEINE

The main body of the seine is made of $\frac{1}{2}$-inch (13 mm) stretched mesh ($\frac{1}{4}$-inch bar) nylon netting, the twine having a diameter of about 0.02 inch (0.5 mm), a tensile strength of about 20 lb (9 kg) and running about 9,000 ft/lb (6,000 m/kg). Continuous-braid nylon netting of similar size mesh opening has also been used satisfactorily, and, since it can be obtained in even smaller mesh size, is preferred where collection of tiny fry is required. A piece of flat, unstretched material about 22 feet (7 m) long by 6 feet (2 m) wide is strung on four doubled lengths of no. 6 (about 3,300 ft/lb (2,200 m/kg)) spun nylon seine twine and puckered to 16 feet (5 m) by $3\frac{1}{2}$ feet (1.1 m). Along top and bottom the netting is mounted nearly square at the outer ends with progressively more pucker introduced towards the middle; along the ends of the netting the

top is mounted square with gradually increasing pucker towards the bottom. This amount of take-up of the netting assures a satisfactory downstream belly when the net is set across flowing water and allows that part immediately behind the foot-chain to lie close to the substrate.

After shaping on the puckering lines the body of the seine is mounted to foot-chain, head-rope and handles. Doubled strands of no. 6 spun nylon twine are used for mounting to foot-chain and head-rope as insurance against a single strand getting chafed through and making the seine unserviceable during operations.

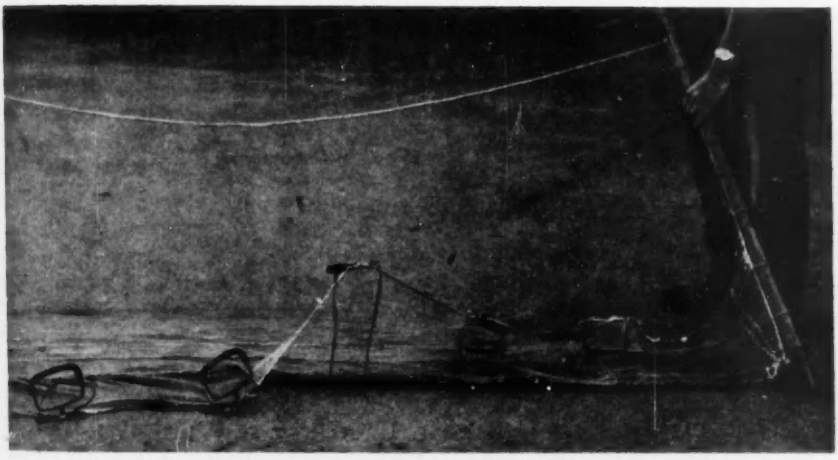

FIG. 1. One end of an apron seine used for studying fish in Maritime salmon streams. Rubber-sheeted apron gate frames near handle are in position for fishing; those to the left are in position for dumping trash from net. Triangular gusset sewed to end of apron strip can be seen at handle.

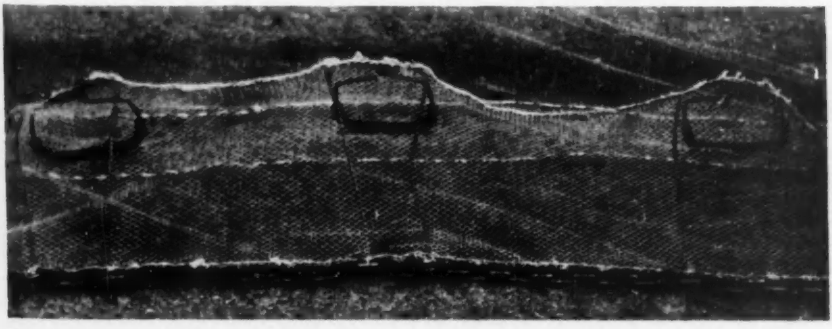

FIG. 2. Apron in fishing position showing how gate frames hold apron away from main net so that fish can swim in under apron. Note chaffing strip sewed under main netting where frames contact it. Netting is secured only to every second link of foot-chain, and this course of links includes those to which gate frames are fastened; chain is laid out without twists, thus assuring maximum flexibility.

The lower edge of the netting is lashed by a series of clove hitches to every second link of the foot-chain, i.e., to all those links lying in a single plane when the chain is laid out with no twists. This course of links must be the same as that into which the gate frames are attached. The netting is mounted under the gate frames, but to the same arm of each link as the frames. Fastening the net in this way assures good flexibility to the foot-line permitting the net to lie close to the irregularities of stream bottom.

The upper edge of the netting is mounted by clove hitches at 1-inch (2.5 cm) intervals to a piece of $\frac{3}{16}$-inch (5 mm) nylon rope a little over 30 feet (10 m) long. Seven feet (2 m) or a bit more of this rope extend beyond the ends of the shaped netting. After the upper edge of the net is fixed to it, each end of this rope is passed through a hole drilled through its corresponding handle in the same plane as eye-bolt for foot-chain, but $3\frac{1}{2}$ feet (1.1 m) up the handle. The upper edge of the net contacts the handle on the same side as the eye of the eye-bolt. The end of the rope is brought around the back of the handle and secured firmly to the main head-rope with a clove hitch.

The remaining end of this rope is then brought down along the handle. About every 4 inches (10 cm) it is wound once around the handle, threading it through the end meshes of the net to bind both meshes and puckering string tightly to the handle with a series of half hitches. The final tie is made into the end-link of the foot-chain, drawing it taut up along its handle.

At this stage, or later, a 6-inch (15 cm) wide "chaffing" strip of netting should be sewed on the under side of the main net along the line where the apron gates will contact it. This reinforcement will take most of the wear in operation and is much more easily replaced than the main netting.

(3) Apron

The netting for the apron requires some puckering, but not as much as the main body of the seine. Without any pucker it will be forced into a vertical position when the net is set in swift water, making setting difficult and hindering fish from moving on to the belly of the net. For a 16-foot (5 m) seine a 20-foot (6.2 m) strip of netting about 1 foot (30 cm) wide is used. An inverted triangular gusset is sewn to each end of this strip to extend the upper edge of the apron strip lengthwise 3 or 4 inches (8 or 10 cm) at each end. This strip is then strung on light twine for puckering to size. Two strands of no. 6 may be used for the bottom edge but a strand of heavier cord (no. 30 spun nylon, about 600 ft/lb or 400 m/kg) is advisable for the upper edge. The lower edge is puckered to the same length as the seine (i.e., 16 feet) using slightly more gathering towards the middle than at the ends. The upper edge is puckered evenly with the lower, the bases of the inverted gussets assuring an extra 6 or 8 inches (15 or 20 cm) length to the top edge. It is not necessary to run lines through the ends of this apron strip. This apron strip is laid *over* the gate frames. The ends of the apron strip, which now include the gussets, are lashed by a series of clove hitches about $\frac{1}{2}$ inch (13 mm) apart to the lower 12 inches (30 cm) of the ends of the main net and of the $\frac{3}{16}$-inch (5-mm) rope binding the main net to the

handles. The free, upper edge of the apron strip is similarly lashed to its own puckering line and to those parts of the arms of the gate frames which are parallel to and directly over the rectangular loops. In securing this edge of the apron to the gate frames, the extra length provided by the gussets is utilized entirely between handles and nearest loop. The bottom edge of the apron is lashed at about $\frac{3}{8}$-inch (1-cm) intervals to the bottom edge of the main netting, including in the lashing those links of the foot-chain to which the main netting and gate frames are fastened.

The rectangular wire loops now assure that even in swift water there will be enough clearance between apron and main netting that fish can readily swim into the space between the two. The gussets and the extra slack provided by them at the end of the apron allow the upper edge of the apron to be pushed by water pressure back against the main netting near the handle. This effectively

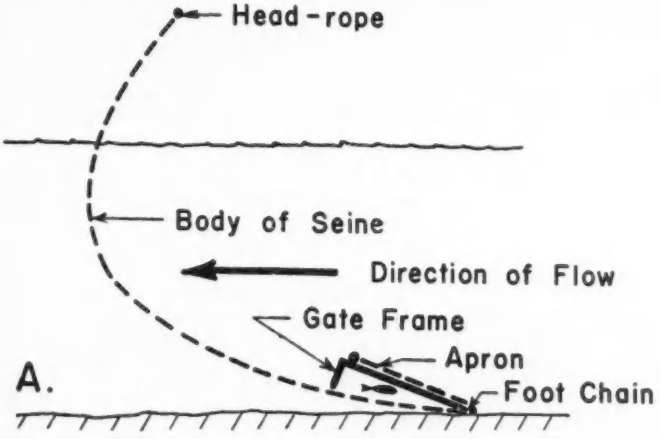

FIG. 3. Profile diagram of the apron seine in action.

forestalls escape of fish which may run lengthwise under the apron to the end of the net. It also facilitates spilling of accumulated trash when the net is turned over because this slack allows the apron to flop away freely from the main netting. Note that neither apron nor its gates are attached to the rest of the net anywhere except along foot-line and handles.

USING THE APRON SEINE

A little experience contributes greatly to the ease and efficiency with which this seine can be operated in swift water.

SETTING. The net is operated by two men, one at each end. These two netmen position the seine across the direction of water flow and facing upstream. They then allow the lower ends of the handles and the foot-chain to drop in upstream of themselves. Water pressure pushes handles and net downstream, forcing them against the stream bottom. Often it is sufficient just to support

the tops of the handles in one hand, but in very swift water some additional upstream pressure on the handles may be necessary. Before dropping the net into the water the handles must first be brought sufficiently close together to allow the foot-chain enough slack that it can conform to stream bottom contours. More slack is required in swifter water, where the chain will be pushed back in an approximate parabola by water pressure.

GETTING FISH ON TO THE NET. Direct current electrofishing techniques have been used almost altogether for bringing fish on to the net. Those in a condition of galvanotaxis can be "led" over the net; in swift water many fish narcotized by the electric current will be carried on to the seine by water flow, but will recover and swim up under the apron as they are released from the electrical field. Under some conditions driving fish by creating a disturbance of the bottom and in the water with staffs has given useful results. Staffs for such work can, to advantage, be shod with steel ferrules and have a short right-angled hook, for turning over stones, fastened into their lower ends. Such "driving" is, however, generally less effective and always much more strenuous work than using electrofishing aids.

Whatever the system for getting fish on to the net, it usually pays to restrict electrofishing or driving to an area within about 15 feet (5 m) immediately upstream of the net and then to make a fresh set to cover additional territory. Otherwise a large proportion of disturbed fish may escape into areas already fished over. As a general rule, successive sets are made moving across the stream, then down or upstream to another traverse. Downstream progression is often used, with some fish being taken against the lower barrier net in barred-off areas with swift water.

LIFTING. Lifting the seine to remove trapped fish is accomplished most efficiently and with least physical exertion if the netmen concentrate on tightening the foot-chain and simultaneously slicing the chain *forwards* (upstream) *and upwards* (to the surface) through the water. Tightening is accomplished by having the hands well spread apart on the handles, pushing with the upper hand and pulling back with the lower, meantime pulling the whole net in opposition to the other netman. At this moment no attempt is made to lift the net clear of the water. As the foot-chain clears the water, fish under the apron run back into the belly of the net which can now be lifted and drained with a minimum of effort. Attempting to lift up the net bodily through the water requires great physical exertion and results in a slow lift with more fish escaping before the foot-chain clears the water.

ACCESSORY DIP NETS. Once the seine is lifted clear of the water it is convenient to remove any fish caught by dipping them off the seine with small shallow dip nets. These "scap" nets are also used during electrofishing operations for catching some narcotized fish near the anode. Small steel spades are welded to the outer ends of the bows of these nets and protect the netting from abrasion when the nets are occasionally used for picking up narcotized fish from between rocks.

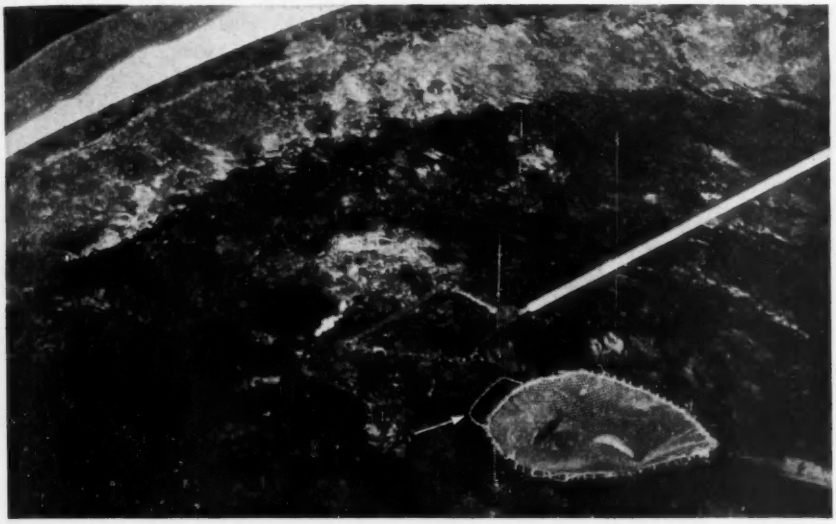

FIG. 4. Close-up of net fishing; apron can be seen through water. Diamond-shaped positive electrode (for 400 volts DC) is usually used for driving or leading fish into scope of seine. Shallow dip net may, as shown, be used for gathering some fish; steel spade (white arrow) welded to outer end of bow of net facilitates picking up some narcotized fish which have settled to bottom, perhaps between rocks.

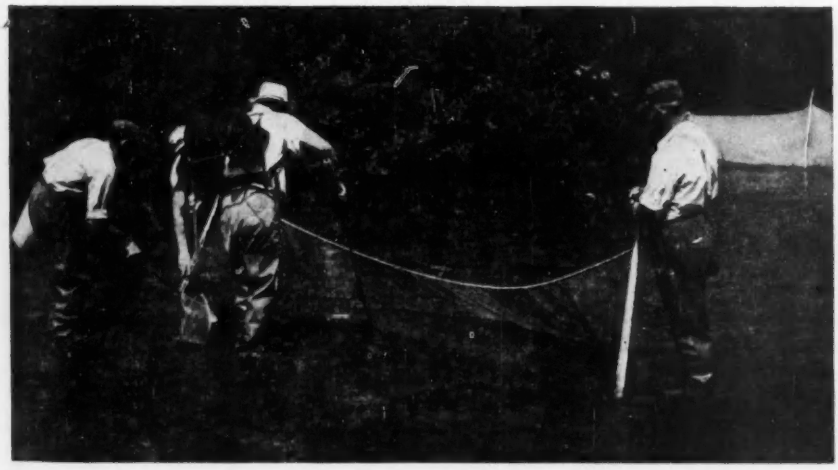

FIG. 5. The apron seine being used in an electrofishing censusing operation. Netman on left is positioning lower hand to lift seine. When footing is at all insecure, as in rough or deep water, electrode man carries a staff in left hand rather than a dip net; this is an important safety precaution. Barrier net in right background is one of a pair used to restrict movement of fish within sampling area during the censusing.

SWEEPING WITH THE APRON SEINE. While a bit cumbersome for the purpose, this apron seine has also been used for a limited amount of sweep-seining in small pools and channels. Care must be taken that the apron remains in proper position, and for this kind of operation one or more of the gate frames may be tied to the main netting.

ACKNOWLEDGMENT

The apron feature of this seine was developed by the technical staff of our Atlantic salmon investigations on the Pollett River, N.B., Messrs P. R. Graves, H. P. Barchard, L. R. MacFarlane and A. G. Steeves. Photographs for Figures 1 and 2 and the diagram (Fig. 3) were done by Mr P. W. G. McMullon. I thank these gentlemen for their contributions.

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Hydrographic and Meteorological Factors Affecting Shellfish Toxicity at Head Harbour, New Brunswick[1]

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ABSTRACT

Toxicities recorded from 1944 to 1958 in blue mussels (*Mytilus edulis*) from Head Harbour, N.B., are examined in relation to some hydrographic and meteorological factors. Within-year variations in toxicity are correlated with summer rises in water temperature. Year-to-year variations are directly correlated with springtime insolation and salinity and inversely correlated with springtime river discharge and winter water temperature. The probable role of these factors in regulating the abundance of the causative organism, hence, levels of toxicity, is discussed.

INTRODUCTION

Incidents of paralytic shellfish poisoning are reported as early as 1793, mostly from Europe and North America, and to a lesser extent from Africa and Australia. Most early records are case histories of human illnesses and fatalities after shellfish consumption. Later records include investigations of species of shellfish involved, incidence of outbreaks, sources of poison, pharmacological and pathological effects of the poison, and control methods. There have been suggestions that outbreaks of poisonings are regulated by tides, currents, temperature, weather conditions, coastal topography, and the location of shellfish beds (Sommer and Meyer, 1937; Medcof *et al.*, 1947; Needler, 1949; Magnusson and Carlson, 1951; Anderson, 1958; Waldichuk, 1958). But there have been few attempts to show that outbreaks follow well defined patterns and are related to some environmental factor or factors.

Paralytic shellfish poisonings from consumption of soft-shell clams (*Mya arenaria*) and blue mussels (*Mytilus edulis*) have been reported from two areas on the Canadian Atlantic coast—the middle and lower reaches of the estuary of the St. Lawrence and the middle and lower reaches of the Bay of Fundy. They have been the joint concern of the Fisheries Research Board of Canada, the federal and provincial Departments of Fisheries, and the Department of National Health and Welfare since 1943. A control and management scheme had already been worked out for the Bay of Fundy and was in effect in 1945 when the New Brunswick and Nova Scotia outbreaks of poisonings occurred. A system of control for the St. Lawrence area was instituted after the fatal outbreak in 1948

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in the province of Quebec and was in force when the next outbreak took place in 1954.

It was not until 1957 when serious outbreaks occurred on the Atlantic (New Brunswick) and the Pacific (British Columbia) coasts that the gravity of paralytic shellfish poisoning as a public health problem was fully appreciated. Since then it has been recognized that there is an urgent need for a better system of control which would permit annual predictions of (1) the time when the shellfish become toxic, and (2) the toxicity levels to be expected. Those who have given the problem most thought agree that such a system should be based on an understanding of the relationships between environmental conditions and the causative organism.

The most complete records of shellfish toxicity on the Atlantic coast are those for blue mussels from Head Harbour, Campobello Island, New Brunswick (Fig. 1). On the basis of records compiled since September 1943, Head Harbour is considered sufficiently representative of conditions in the Bay of Fundy to serve as a key station for the whole region (Medcof, MS 1949). In the present paper an attempt has been made to examine annual and seasonal variations in mussel toxicity at Head Harbour from 1944 to 1958 in the light of some hydrographic and meteorological conditions. It was hoped that such an examination would provide information on the merits of various environmental indices on which long-range predictions of toxicity levels might be based. The tentative conclusions from this study are being used as guides in planning further field and laboratory studies of the peculiarities of the life history of the causative organism and we hope that they may stimulate similar investigations in other affected areas.

MATERIAL AND METHODS

From 1943 to 1952, samples of Head Harbour mussels were collected and their extracts prepared by the Fisheries Research Board's Biological Station at St. Andrews, N.B. (Medcof, unpublished records). Since 1953, the Fisheries Protection Branch and the Fish Inspection Laboratory of the Department of Fisheries at St. Andrews, N.B., have assumed this responsibility (Bond, unpublished records).

Bioassays on all shellfish extracts were made by the Department of National Health and Welfare's Laboratory of Hygiene, Ottawa, using a modification of a procedure originally described by Sommer and Meyer (1937). Toxicities were formerly expressed in mouse units (*m.u.*) but now in micrograms (μg) of purified poison per 100 grams of shellfish meat (Table I). Use of the latter unit was agreed to in 1955 at a joint Canada-United States conference on shellfish toxicology because it makes bioassay results from the various laboratories directly comparable.

Mouse units may be converted to micrograms by applying the following formula:

$$m.u.(\mathrm{CF}) = \mu g$$

where CF, the conversion factor, is the number of micrograms of poison equivalent to one mouse unit. This factor varies appreciably from mouse strain to

mouse strain as shown by tests with a standard extract. For the mouse strain used at the Laboratory of Hygiene, Ottawa, the conversion factor is 0.16. Toxicity scores less than 32 μg (200 *m.u.*) cannot be measured accurately by the usual bioassay technique and have been taken as 32 μg for the purpose of calculating mean toxicities in this study.

The Fisheries Research Board's "Prince" Station No. 5 (Lat. 44° 56′ 48″ N, Long. 66° 48′ 41″ W; Fig. 1) was selected to provide water temperature and salinity data because of its proximity to Head Harbour and the availability of monthly hydrographic records since 1944. Hydrometric data for the St. Croix

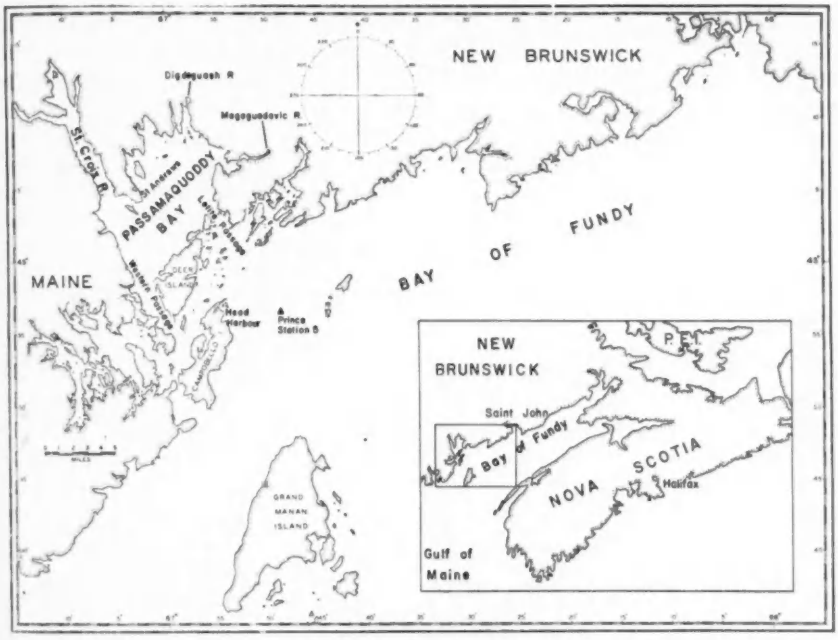

FIG. 1. Western part of Bay of Fundy showing location of Head Harbour, "Prince" Station No. 5, and major drainage areas.

and Magaguadavic Rivers were obtained from the Atlantic Drainage Records of the Department of Mines and Resources. Monthly records of meteorological observations conducted by the Department of Transport provided the data on duration of sunshine at Saint John, N.B., to the end of 1957.

FACTORS INFLUENCING MUSSEL TOXICITY

WATER TEMPERATURE

Of the many factors suspected of influencing seasonal and annual fluctuations in shellfish toxicity levels, temperature has been given the most considera-

tion. A characteristic feature of shellfish toxicity in the Bay of Fundy is its annual recurrence during summer months. This has prompted an examination of within-year and year-to-year variations in toxicity levels in relation to surface water temperature at St. Andrews and "Prince" Station No. 5.

WITHIN-YEAR (SEASONAL) VARIATIONS. Surface water temperature data collected monthly between 1944 and 1958 from "Prince" Station No. 5, when plotted, show characteristic sinusoidal curves with maxima (11 to 13°C) in August and September and minima (1 to 3°C) in February and March. Although Head Harbour may be affected the year round, the peak toxicity scores are reached between July to October. Figure 2 shows seasonal variations in monthly toxicity in relation to monthly surface water temperature, both averaged for 15 years. Evidently the toxicity levels for August and September are two to three times as high as those for the rest of the year and are coincident with the attainment of higher summer water temperatures. In spite of this clear relationship, the build-up and fall-off in toxicity are much more sudden than those for temperature and the lowest scores (poison usually undetectable <32 μg) hold almost steady throughout the winter and spring (November to May) quite independent of considerable changes in water temperature (Fig. 2). Factors other than temperature appear to be at work here.

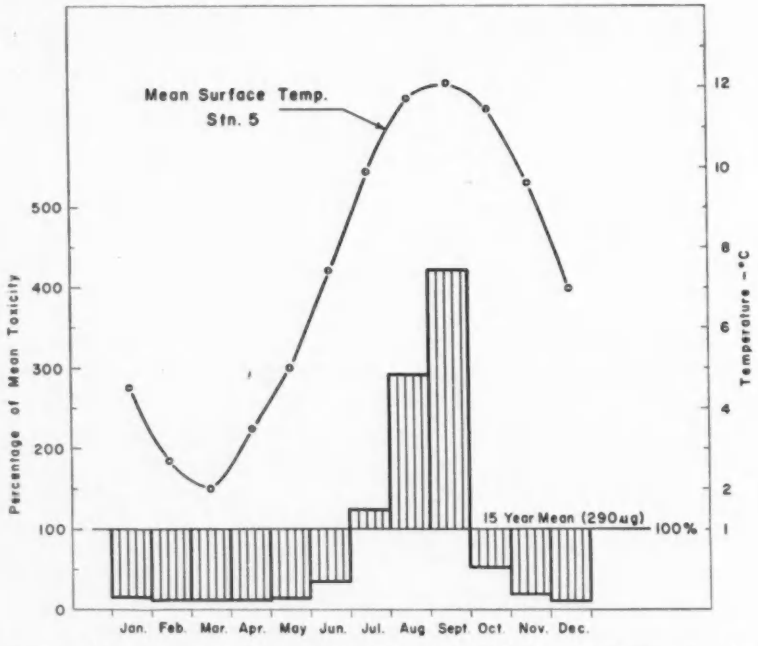

FIG. 2. Seasonal variations in mussel toxicity at Head Harbour in relation to surface water temperature. Mean monthly toxicity expressed as a percentage of 15 years' mean (1944–58).

YEAR-TO-YEAR VARIATIONS. A close correlation exists between the summer water temperatures and toxicity levels on a within-year basis. However no such correlation is seen on a between-year basis; i.e., highest toxicity scores do not occur in the warmest summers and vice versa. This suggests that high water temperature may play an important part in stimulating toxin accumulation but that the level of toxicity in any particular year is governed by other factors.

In contrast there is an inverse correlation between mean winter (January to March inclusive) water temperature and mean toxicity score in the summer months following (June to October inclusive). This has been demonstrated before by Bond (MS, 1958) and Medcof (1960) using surface water temperature records at the Biological Station, St. Andrews, N.B., for the period 1944 to 1956. A similar but even clearer correlation has been demonstrated by using "Prince" Station No. 5 surface water temperatures (Fig. 3 and Table I).

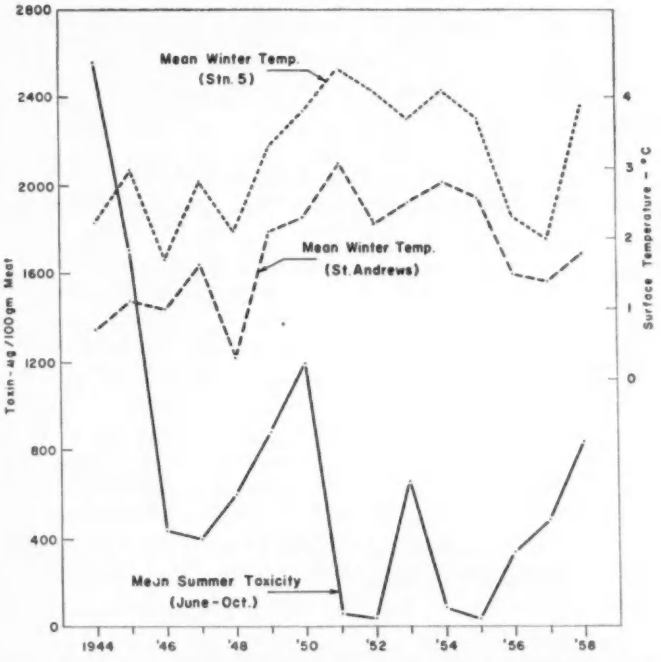

FIG. 3. Mussel toxicity at Head Harbour in relation to mean winter surface temperature.

RIVER DISCHARGE AND SALINITY

Freshwater inflow, especially during spring freshets, has considerable effect on the hydrography of Passamaquoddy Bay and adjacent areas including Head Harbour. Heaviest discharges are from the St. Croix and Magaguadavic Rivers; those of Digdeguash are less important (Forgeron, 1959). The average rates of

TABLE I. Annual variations in mussel toxicity at Head Harbour, N.B., in relation to surface salinity, water temperature and sunshine duration.

Year	Toxicity (unrounded June–October mean)		Salinity (May) "Prince" Station No. 5	Mean surface water temperature (January–March)		Sunshine in May Saint John
				"Prince" Station No. 5	St. Andrews	
	m.u.	*μg*	‰	°C	°C	*hr*
1944	16149	2584	31.26	2.2	0.7	278
1945	10702	1712	30.70	3.0	1.1	166
1946	2687	430	30.86	1.7	1.0	188
1947	2443	391	30.88	2.8	1.6	180
1948	3707	593	30.62	2.1	0.3	139
1949	5408	865	31.33	3.3	2.1	222
1950	7496	1199	31.53	3.8	2.3	259
1951	344	55	30.81	4.4	3.1	194
1952	229	37	30.10	4.1	2.2	170
1953	4133	661	31.31	3.7	2.5	197
1954	506	81	29.61	4.1	2.8	188
1955	236	38	30.21	3.7	2.6	167
1956	2084	333	31.09	2.3	1.5	225
1957	3052	488	31.92	2.0	1.4	237
1958	5249	840	30.39	3.9[a]	1.8	183

[a]Calculated.

discharge for each major drainage area measured from 1943 to 1958 show that the maximum discharge of fresh water into Passamaquoddy Bay occurs in April (Table II).

The most important factors determining the salinity in Passamaquoddy Bay are the relative amounts of fresh and salt water carried into the Bay. River drainage mixes with sea water brought in from the Bay of Fundy by tides and results in lowered salinity of the mixed water in Passamaquoddy Bay. Hachey (1957) deduced that the waters of Passamaquoddy Bay circulate in an anti-clockwise direction and that the mixed, less saline lighter surface waters flow out of the Bay chiefly through Western Passage (Fig. 1). Hachey's conclusions have since been substantiated and extended by drift bottle experiments reported by Chevrier and Trites (1960). The drift pattern indicates an inflow through Letite Passage, a counter-clockwise circulation in Passamaquoddy Bay, and an outflow that passes through Western Passage along the Campobello side of Head Harbour Passage and thence into the "Prince" Station No. 5 area of the Bay of Fundy.

From this circulation pattern, it is easy to understand the correlation between river discharge and the hydrography of "Prince" Station No. 5. Year-to-year variations in the springtime (May) salinity are clearly correlated with variations in river discharge (Fig. 4). Furthermore, high river discharges and low salinities are for the most part correlated with low toxicities, as seen in 1951, 1952, 1954 and 1955. On the other hand, low discharges and consequently high salinities usually coincide with high toxicity scores, as seen in 1944, 1950 and 1953. A conspicuous exception to this is seen for the year 1948 when salinity, river discharge and toxicity were all low (Table II and Fig. 4).

TABLE II. Mean monthly discharge in c.f.s. of St. Croix River (S) and Magaguadavic River (M) from 1943 to 1958. Data from Atlantic Drainage Records of the Department of Mines and Resources.

Year		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Annual mean
1943–44	S	2740	3250	1980	1710	1650	1720	2330	1910	1750	1560	1370	1490	1955
	M	2030	2310	620	327	255	507	2290	1170	811	322	190	508	945
1944–45	S	1770	2220	1750	2140	2000	2570	6050	7550	2100	1915	1560	1720	2779
	M	1370	2070	987	1370	769	2320	4100	3550	1060	442	219	255	1543
1945–46	S	1700	1880	1770	1690	1670	3370	3170	3750	1970	2090	1660	1350	2172
	M	860	1480	898	639	687	2310	2900	2410	611	272	92	77	1103
1946–47	S	1100	858	929	1200	2140	1930	2920	4310	4170	2940	2100	1810	2200
	M	106	418	920	628	1240	1270	2550	2680	2330	700	335	231	1117
1947–48	S	2020	1430	832	628	573	1000	2270	3020	2260	2270	1690	1010	1584
	M	157	221	202	268	322	579	1808	2736	778	558	266	94	666
1948–49	S	777	838	1280	2520	2020	1930	2780	2270	2050	1720	1420	838	1704
	M	120	1260	620	1560	529	1070	2600	1110	430	174	416	546	869
1949–50	S	862	1440	1770	1990	2000	2150	4190	2440	2220	1760	1330	1070	1935
	M	513	1640	2870	1230	834	1180	3660	1170	751	819	573	293	1294
1950–51	S	822	2900	5150	2500	2570	3790	7940	3080	2680	2610	2540	2490	3256
	M	230	2680	4690	3060	1930	2170	3090	1220	610	730	650	610	1806
1951–52	S	2150	3020	1960	2840	2960	3400	4770	2440	3930	2040	1780	1430	2727
	M	772	1310	1730	2300	1300	1170	3400	1370	1760	175	444	344	1340
1952–53	S	1630	1050	1370	1390	2320	3460	4660	2990	2360	1940	1730	1200	2175
	M	517	644	553	802	1890	2780	3530	1680	472	712	347	392	1193
1953–54	S	1050	1960	3100	2300	2350	2520	7390	3900	2890	2410	2510	3460	2987
	M	431	1650	2200	879	1120	1940	4380	1870	1720	1080	770	1490	1627
1954–55	S	2909	3833	5043	3663	4048	4238	5840	2872	2464	2213	2279	1631	3419
	M	1790	2020	2990	1670	1660	1090	3510	1730	746	480	361	209	1521
1955–56	S	998	810	630	1402	1650	2062	3722	3491	2380	1987	1685	1163	1832
	M	133	209	176	1320	663	891	3530	3000	1240	784	248	196	1032
1956–57	S	1176	950	1143	1948	1933	1981	2345	2598	1978	965	1030	933	1582
	M	237	447	785	599	384	753	2150	1410	391	498	455	321	702
1957–58	S	545	1321	2690	2830	2527	2219	4972	4207	2208	2553	2096	1755	2494
	M	146	1000	2650	2400	929	1330	3500	2040	777	715	643	533	1389
Mean discharge into Passamaquoddy Bay		1055	1571	1810	1660	1564	1990	3745	2666	1730	1314	1093	982	

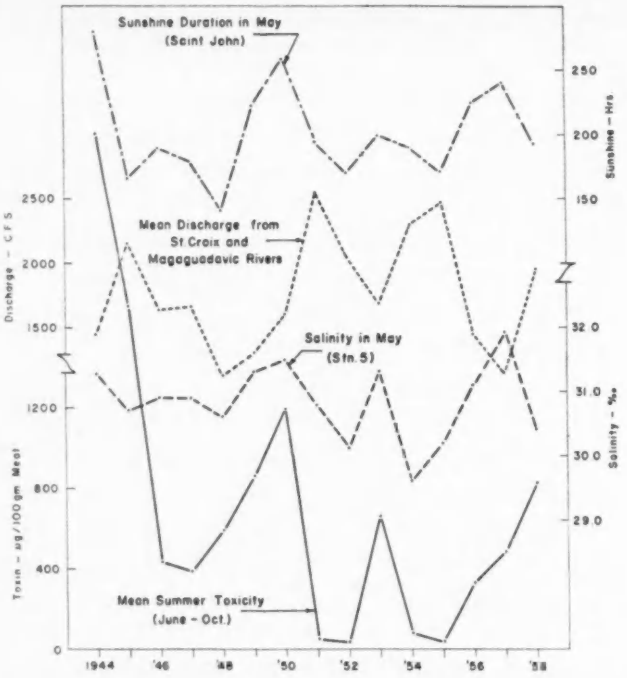

FIG. 4. Mussel toxicity at Head Harbour, in relation to annual river discharge, salinity and sunshine duration.

SUNSHINE DURATION

Duration of sunshine before the onset of toxicity period, i.e., in the month of May, shows a positive correlation with toxicity scores (Fig. 4). Records of sunshine hours each month at Saint John, N.B., from 1944 to 1958, show that the years 1944, 1950, 1953 and 1957 had more sunshine than other years. These are also the years when summer toxicity scores were high. The only exception is seen in 1958 when high toxicity did not show a good correlation with sunshine duration. The only other known association between shellfish toxicity and sunshine is that reported by Anderson (1958) who showed that there was unusually great insolation prior to the 1957 outbreak of poisonings in British Columbia.

STATISTICAL TREATMENT

Interrelationships of toxicity and the various environmental factors which operate either individually or in combination are difficult to assess or describe by the simple graphical methods used above. And the correlations demonstrated can be misleading when we come to interpret them. Nevertheless, our preliminary examination suggests that winter water temperature, river discharge and/or salinity and sunshine just prior to the onset of toxicity are important in regulating year-to-year differences in toxicity. As pointed out in the next section,

these relationships have possible biological explanations. Preliminary trials showed that the closest relations seem to be between toxicity and January–March water temperature, May salinity, and May sunshine, and these data have been selected for multiple correlation analyses (Snedecor, 1946). The results (Table III) indicate the degree to which toxicity level may be affected by these three factors, independently or in combination. Only the simple correlation coefficient for sunshine ($r = 0.5261$) is significant at the 95% probability level[2].

TABLE III. Correlations of toxicity with winter temperature, May salinity, and May sunshine, and standard partial regression coefficients of the multiple correlation analysis.

	Temperature r	Salinity r	Sunshine r	Total R
Degrees of freedom	13	13	13	11
Correlations, r and R	−0.3057	+0.4127	+0.5261	+0.5708
Standard regressions	−0.2433	−0.0567	+0.5223	...

Analysis of the combined effects of these factors gives the standard partial regression coefficients shown in the last line of Table III. The product of each of these with the correlation immediately above it represents the contribution of each factor to R^2, the square of the multiple correlation. It is evident that salinity contributes nothing (the product is negative) to the total effect; hence its fairly large simple correlation (0.4127) is merely a chance by-product of the correlation between sunshine and salinity. The total correlation coefficient, $R = 0.5708$, was not significant at the 95% level.

Thus, of the factors studied, only May sunshine has a statistically demonstrable relationship to toxicity, which is estimated to account for about 28% of the total variability ($= 0.5261^2$). The effect of winter temperature, if it is real, contributes another 9%. There is still a great deal of residual variation. Perhaps this is because we are not making our observations with sufficient precision, or perhaps we are disregarding important factors that should be included in the analysis.

DISCUSSION AND CONCLUSIONS

Sufficient indirect and circumstantial evidence has accumulated to implicate photosynthetic marine dinoflagellates of the genus *Gonyaulax* as the source of toxicity in shellfish (Sommer *et al.*, 1937; Needler, 1949; Riegel *et al.*, 1949). This case is strengthened by recent experimental work which shows that clam

[2]To complete the analysis, the simple correlation coefficient between winter temperature and May sunshine is −0.1722, non-significant as expected. The correlation between temperature and salinity is −0.4856, which borders on significance, and it is possible that winter temperature might be correlated with factors that affect salinity, though this has not been demonstrated to date. The correlation between May sunshine and May salinity is +0.6725, significant at the 1% level, but here again the mechanism involved is obscure as yet. However, the fact that a selection was made of temperatures, etc., from among a number of possible months, gives these and the other significance levels quoted a formal character: additional years' data will be needed to really substantiate them.

and mussel toxin is identical with that produced by *Gonyaulax* and there is no longer room for reasonable doubt that the shellfish derive their poison from this dinoflagellate (Burke *et al.*, 1960; Murtha, 1960; Schantz, 1960).

In the Fundy area, studies conducted by Medcof *et al.* (1947) and Needler (1949) indicate that periodic increases in the abundance of *Gonyaulax tamarensis* coincide with the appearance of high toxicities. With this evidence in hand, we are inclined to believe that the correlations demonstrated or suggested in the present study are not coincidental but indicate causal relationships, i.e., the environmental factors have a controlling effect on the causative organism and thus on the toxicity.

We hold this view even though our statistical analysis of available information points to sunshine as the only factor whose significance is beyond reasonable doubt. The analysis does not rule out the possible importance of the other two. And it is appropriate at this point to set forth the rationale for this belief because we are now planning studies of the biology of the causative organism. We may also speculate, in the light of what we know or can deduce, on how this environmental control is effected. We base our thinking on two assumptions, first, that fluctuations in toxicity levels are the result of fluctuations in the abundance of the causative organism and, second, that *Gonyaulax* shares the essential life history features of typical chromatophore-bearing dinoflagellates and undergoes encystment under unfavourable conditions and passes the winter in this state in bottom sediments.

A. B. Needler (1949) examined shellfish toxicity at Head Harbour in relation to summer surface water temperature from 1944 to 1947 and indicated that *G. tamarensis* may appear any time after the temperature reaches 10°C. She suggested that it is the warming of the water as well as the absolute temperature which stimulates reproduction. From Bond's (MS, 1958) correlation, which is supported though not yet wholly confirmed by subsequent data, it appears that winter as well as summer water temperatures deserve a critical examination in our renewed investigations. Low temperature has been known to favour encystment of dinoflagellates and it seems that the causative dinoflagellates remain encysted until threshold excystment (summer) temperatures are reached.

River discharge shows a negative correlation with Head Harbour toxicity and there are several ways in which it may affect abundance of the causative organisms. It may remove them from the region by direct flushing. Or it might create salinity conditions favourable or unfavourable to *G. tamarensis*. This latter seems doubtful, however, because this species is considered to be an estuarial euryhaline species (Lebour, 1925). River discharge may also regulate *Gonyaulax* and toxicity through its effects on the transparency of water to light.

Like many other dinoflagellates, *Gonyaulax* depends on sunlight for its photosynthetic activities and it is not surprising that the clearest of all our toxicity correlations is that with sunlight. Gran and Braarud (1935) have indicated that in the Fundy region the month of May is critical in determining year-to-year differences in the total spring sunshine budget and hence in determining phytoplankton population abundance. It is in May that phytoplankton

production is maximum. The same authors show that in their spring freshets the St. Croix, Magaguadavic and Digdeguash Rivers carry large amounts of silt into Passamaquoddy Bay and make the water at "Prince" Station No. 5 very turbid in April and May. This affects its transparency and the depth of the photic zone. Presumably this also affects *Gonyaulax* because years of poor solar radiation and high turbidity (high river discharge) are also years of low toxicity. Needler (1949) has suggested that concentration of diatoms in the surface layers may hamper production and survival of *Gonyaulax* by reducing water transparency.

In their generalizations, Gran and Braarud (1935) state that the abundance of phytoplankton in the Bay of Fundy depends on the turbulence, transparency, and surface illumination of the water, on the passive sinking of the phytoplankters themselves to depths beyond the photic zone and on the grazing action of the zooplankton population. Evidence is insufficient to show which of these factors are the most important in regulating abundance of dinoflagellates, but so far the correlations demonstrated in this study agree with Gran and Braarud's conclusions and in some points may extend them, for example, in pointing to the possible importance of winter water temperature. We intend to give special attention to many of these factors in our search for a method of long-range prediction of shellfish toxicity conditions.

ACKNOWLEDGMENTS

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Growth and Reproduction of the Longnose Sucker, *Catostomus catostomus* (Forster), in Great Slave Lake[1,2]

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ABSTRACT

A biological investigation of the longnose sucker, in Great Slave Lake, was carried out in 1950 and 1951. Specimens were obtained by use of gill nets and seines. Suckers taken along the south shore had a faster rate of growth than those in the more northern area. In both areas, males and females grew at the same rate in length and weight. Females lived longer and thereby became heavier. The average annual survival rate was 45%. The growth exponent was 2.88; the length-weight relationship, $W = 0.000252\ L^{2.88}$. Longnose suckers spawned in Hay River from the ice cover break-up in May to June 15. The water temperature did not exceed 59°F (15°C). The majority of spawning-run fish were 10 to 12 years old. Although sexually mature at 7 years, no suckers younger than 9 years of age were found in the spawning run. Females contained from 17,000 to 60,000 eggs but may not spawn each year. Fingerlings from Hay River were 33 to 80 mm in length, and were in their first summer. They all had scales.

INTRODUCTION

Investigations in 1944 to 1947 demonstrated that lake trout, *Cristivomer namaycush*, lake whitefish, *Coregonus clupeaformis*, and ciscoes, *Leucichthys* spp., dominated the fish population of Great Slave Lake (Rawson, 1951). The first two species now support a gill-net fishery (Kennedy, 1956).

The longnose sucker, *Catostomus catostomus* (Forster), ranked fourth by numbers and fifth by weight from experimental nets. The food of lake whitefish and the longnose sucker is similar, but the latter was not considered a serious competitor because of the numerical superiority of the whitefish (Rawson, 1951). As a result of preferential commercial fishing, the relative numbers of these species could be altered.

To ascertain some aspects of the biology of the longnose sucker and to provide a comparison for future investigations, material was collected during the summers of 1950 and 1951.

MATERIALS AND METHODS

Methods of Sampling

Specimens for the growth analysis were obtained by use of gill nets. Seines, used only in shallow water (less than 1 m) on two occasions, caught only finger-

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lings. During 1950, the fish came chiefly from commercial nets which had a mesh size of 5½ inches stretched measure (2¾ inches bar measure). Fish also were taken in 3 or 4½ inch mesh nets. The following summer light-weight cotton nets were used. These nets, each 50 yards (46 m) in length and of various mesh sizes, greatly extended the size range of fish taken. Excluding fish caught in the Hay River, a total of 624 fish were obtained by gill nets (Table I). Eighty per cent were from 5½ inch mesh nets and were mainly donated by the commercial fishermen. A good deal of overlapping of sizes taken in successive meshes was noted and a wide range of lengths was obtained.

TABLE I. Average size of Great Slave Lake longnose suckers caught in experimental and commercial gill nets. Fish caught in the Hay River are not included.

Mesh size		No. of fish	Length	Weight
in	*mm*	*no.*	*mm*	*lb*
1½	38	13	163	0.1
2	51	19	240	0.4
3	76	33	338	1.2
4	102	47	408	1.9
4½	114	5	442	2.3
5	127	10	457	3.0
5½	140	497	502	4.0
Total		624		

DISTRIBUTION IN AREA

The longnose sucker is unevenly distributed over the lake. Rawson (1951) found it most numerous along the southwest shore and in Yellowknife Bay. It occurs most frequently in the commercial fishery along the south and west shore (Kennedy, 1956). No attempt was made to collect specimens from the entire lake; sampling was confined to some regions of apparent greatest abundance (Fig. 1).

For comparative purposes, 532 specimens, taken from the area between Fish Point and Slave Point, were considered as a southern population. The 194 fish taken between Caribou Bay and Gypsum Point, including 17 from the Gros Cap area, were regarded as a northern population. Isolated catches were also recorded.

DISTRIBUTION IN DEPTH

During both summers of the study, longnose suckers were taken at all depths from 4 to 80 feet (1–24 m). They were present in commercial catches of lake trout and lake whitefish during the entire season (June 15 to September 15). Table II tabulates various information on the specimens.

EXAMINATION OF SPECIMENS

The growth of 726 individuals was investigated. Immediately after capture, the fork length was measured in millimeters and the weight in pounds. Scales

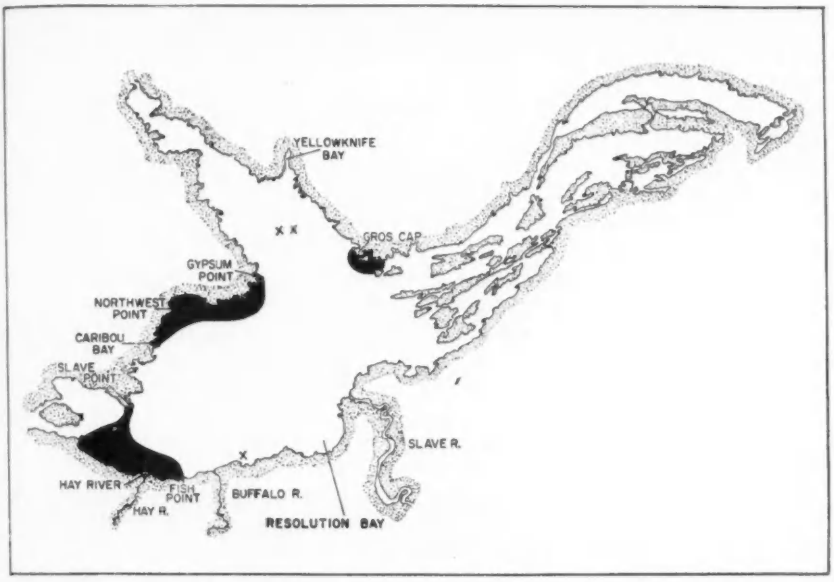

FIG. 1. Map of Great Slave Lake showing the general location of longnose sucker samples. The samples from Fish Point to Slave Point are considered, for comparative purposes, as a southern population; the others, a northern population.

TABLE II. Depths and dates at which longnose suckers were taken in Great Slave Lake.

Date		Depth		Locality
1950	1951	*feet*	*metres*	
June 28	...	50–80	15–24	Burnt Point
June 28–30	Aug. 15–21	18–30	5–9	Hay River
July 17–26	July 1–9	30–60	9–18	Northwest Point
July 17	...	25–48	8–15	Caribou Bay
July 20–31	July 1–9	30–60	9–18	Moraine Point
July 27	July 16–30	4–65	1–20	Long Island
Aug. 11–24	...	20–50	6–15	Fish Point
...	Aug. 13	30–40	9–12	High Point
...	Aug. 7–18	60–60	18–18	Slave Point
...	Aug. 18–20	44–60	13–18	Hay River

were taken from the center of the body, on the left side, above the lateral line. Determination of sex was difficult in suckers less than 350 mm, except in a few individuals. Fish under this size were classified only as immature.

Age Determination

Scale impressions were made on plastic slides with a press made from a notary seal. Age was determined by counting the annuli under a binocular microscope. Annuli were detected by the presence of incomplete circuli, erosion and cutting over. The annuli were most discernible in the anterior field, but cutting over was best seen along the posterolateral scale radii. The interpretation was checked by projecting the images of the scale impressions. The age was recorded in completed years; thus, a fish of age-group 11 (11 annuli) would be actually in its 12th summer.

In order to insure consistency for a comparison with the growth of the longnose sucker as reported by Rawson (1951), Dr Rawson kindly provided his scale samples. These have been examined so that the age assignments are comparable.

Sampling of Spawning Run

Local residents reported that large numbers of longnose suckers appear in the Hay River immediately after the spring break-up of the ice cover. An attempt was made to catch some in 1951. That year break-up was late, with flood conditions present until the third week in May. Four gill nets, each 50 yards long, were placed in the river (Fig. 2). Net No. 1 was situated across the main (East)

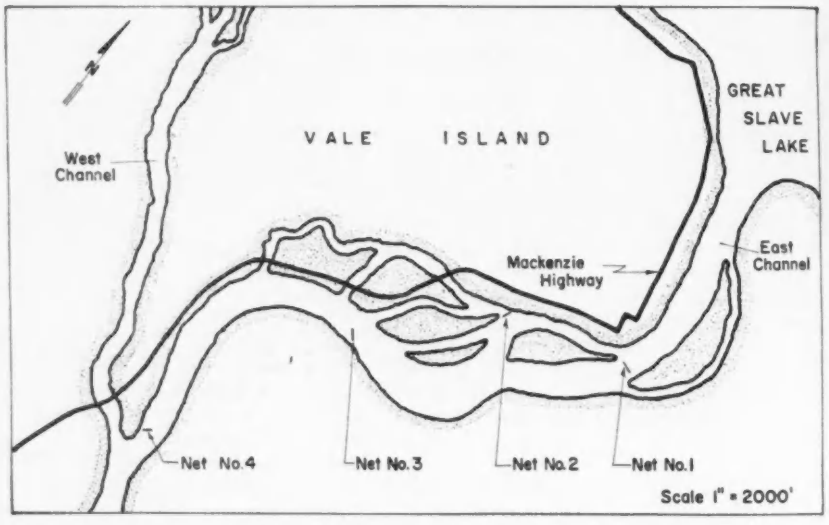

Fig. 2. Location of nets at the mouth of the Hay River to sample the spawning run of longnose sucker in 1951.

channel, 1 mile (1.6 km) from the river mouth. It was set by Mr H. Camsell for dog food. He provided a daily record of the catch of longnose suckers. These fish were not examined by the author. Net No. 2 was at the downstream

point of an island but was not in the main current. It failed to catch any suckers and has been disregarded in the analysis. Net No. 3 was in a backwater at the foot of a rapids, a mile upstream from Net No. 1. Net No. 4 was above the rapids, 1 mile above Net No. 3. This point is 30 miles (48 km) below Louise Falls, an impassable barrier to fish, 52 feet (16 m) high. Spawning might take place anywhere downstream from the falls.

In all, 195 fish were caught; 114 were examined. The nets' efficiency was reduced by clogging with river-borne debris.

The longnose suckers in the spawning run were divisible into 3 groups according to the state of their gonads (Larimore, 1957). The female gonads were in 3 fairly distinct states: *latent*, in which the ovaries were small, firm, white in colour and contained small (1.5 mm in diameter) granular eggs; *spawning condition*, in which the ovaries almost completely filled the abdominal cavity (Fig. 3) and were distended with yellow, opaque, large (3.0 mm) eggs which flowed easily when pressed; *spent*, in which the ovaries were flaccid, fatty, yellow-orange

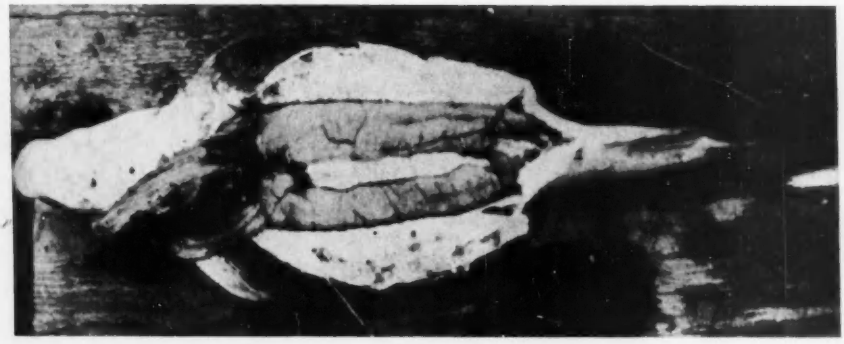

FIG. 3. Appearance and size of ovaries of a female longnose sucker in spawning condition.

in colour and contained many congested blood vessels. The male gonads were in 2 quite distinct states: *spawning condition*, in which the testes were white, opaque, highly convoluted and readily exuded milt when pressed; *spent*, in which the testes were smaller, harder in consistency and rubbery to the touch.

Females in spawning condition had a green-gold dorsal surface. Along each side was a red-pink coloured band divided by the lateral line. This band presumably is a spawning characteristic as it is much less noticeable later in the summer. Males in spawning condition were similar in appearance, but had darker dorsal sufaces and the coloured band along each side was bright pink. Nuptial tubercles, or pearl organs, were prominent along the rays of the anal and caudal fins. These appeared to be indicative of a male in spawning condition, as they were hardly noticeable later in the summer. They were less prominent in spent males.

GROWTH

Size Range of Fish Captured in Gill Nets

The smallest sucker taken was 142 mm long, weighed 1 ounce (28 g) and was 2 years old. The largest was 642 mm long, weighed 7.3 lb (3.3 kg) and was 19 years old.

Comparative Growth in Northern and Southern Populations

The average length of the 532 specimens in the southern population are compared by age-groups with the average length of the 194 specimens in the northern population in Table III. A graph of these date definitely indicates that the rate of growth is more rapid in the southern population. This is

Table III. Average size in fork length of longnose suckers from Great Slave Lake. The 1950–51 fish were collected from two regions which are shown in Fig. 1. The 1944–46 fish were collected by Rawson (1951). The numbers of fish are in parenthesis.

Age	1950–51 Northern population		1950–51 Southern population		1944–46	
	no.	*mm*	*mm*	*no.*	*mm*	*no.*
2	(4)	152	179	(3)	158	(3)
3	(2)	170	203	(12)	177	(10)
4	(1)	253	239	(7)	224	(6)
5	(4)	290	306	(4)	248	(6)
6	(3)	314	308	(5)	288	(9)
7	(10)	330	363	(11)	321	(9)
8	(13)	372	412	(19)	386	(9)
9	(31)	403	479	(64)	413	(5)
10	(41)	433	496	(101)	456	(6)
11	(31)	465	496	(128)	474	(12)
12	(14)	499	517	(66)	552	(2)
13	(13)	510	530	(50)	538	(7)
14	(14)	518	541	(32)	...	...
15	(4)	547	557	(18)	...	...
16	(4)	527	575	(7)	...	...
17	(2)	579	586	(5)	...	...
18	(2)	607	...	...	...	...
19	(1)	642	...	...	...	...
Total	194			532		84

especially marked in the 8 to 12 year range, from which most of the specimens were obtained. The south shore receives several rivers (Slave, Buffalo and Hay) that are rich in organic material, which could be expected to make conditions for growth more favorable than in the more oligotrophic northern areas.

Comparison with Specimens Collected in 1944 to 1946

Table III also presents data on the specimens collected by Rawson (1951). Forty-nine of his fish came from near Resolution Bay, 26 from near Yellowknife and the other 9 from 3 other locations (J. J. Keleher, personal communication, 1961). The average lengths at each age generally fall within the sizes established for the 2 populations sampled in 1950-51. Rawson's data consist of fewer fish, taken in different localities and generally from nets of a smaller mesh. Any difference between Rawson's and the author's data could be due to the sampling methods. There is no evidence of a change in growth rate. It is unlikely that 7 years of commercial fishing had any effect on growth, because it was not conducted continuously in the study areas.

Growth of Males and Females

The size of 530 females is compared to the size of 196 males in Table IV. When all age groups are considered, there does not appear to be a consistent difference between the sexes, indicating that they increase in length at about the same rate. Females appear to outlive the males. No males older than 16 years were taken, whereas females as old as 19 years were caught.

Table IV. Average lengths of each sex for age-groups over 6. The sex of 45 fish from age-groups 2 to 6 could not be determined. The number of fish are in parenthesis.

Age	Females		Males	
	no.	*mm*	*mm*	*no.*
7	(17)	349	384	(4)
8	(22)	379	423	(10)
9	(55)	452	459	(40)
10	(98)	477	479	(44)
11	(117)	496	474	(42)
12	(63)	516	506	(17)
13	(44)	534	510	(19)
14	(33)	536	529	(13)
15	(17)	562	526	(6)
16	(9)	568	562	(1)
17	(7)	584	...	...
18	(2)	607	...	...
19	(1)	642	...	...
Total	485			196

Age Composition of Catch

A catch curve — the logarithms of the frequency of occurrence of fish at each age (Ricker, 1958) — is shown in Fig. 4. Although the majority of the fish were taken in 5½-inch mesh, those caught in nets of smaller mesh were also used to derive the curve, but fish less than 11 years old are of course under-represented. The straight descending limb of the curve shows an average

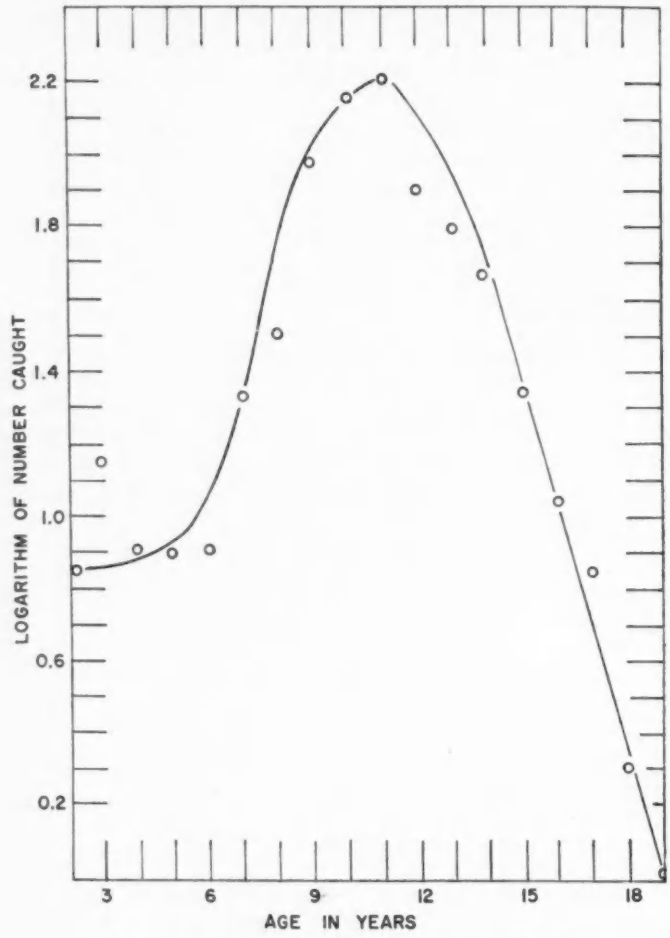

FIG. 4. Catch curve of longnose sucker in Great Slave Lake.

survival rate of 45% each year, after the suckers reached the age of 14 years. The complement of the survival rate represents the annual mortality rate, in this case 55%.

LENGTH–WEIGHT RELATIONSHIP

The weights of male and female suckers were averaged for each 50 mm length interval. Suckers below 350 mm, with one exception, were classed as immatures. The average weights of males and females were almost identical. There was no evidence of sexual dimorphism in weight. No males longer than 600 mm were taken; 13 females exceeded this length. These larger females were heavier than any of the males captured.

The average weight in pounds, calculated for each 10 mm interval of fork length for 639 fish of both sexes, was converted to grams. Fork length was converted to standard length by multiplying by 0.88, the factor being derived from 84 of Rawson's fish. In Fig. 5 the average weights are plotted against the standard lengths.

An equation for the length–weight relationship was calculated by expanding the data and empirically deriving the constant and the growth exponent from normal equations (see Lagler, 1956). The value for the growth exponent was 2.88. The equation, drawn in Fig. 5, is:

$$\text{Weight} = 0.000252\ \text{Length}^{2.88}$$

The 1944–46 data, by similar treatment, expresses the same equation.

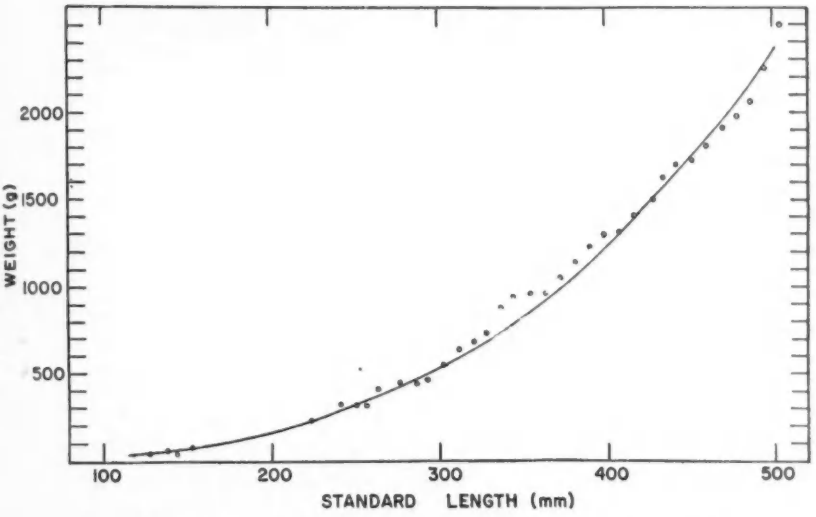

FIG. 5. Length–weight relationship of longnose sucker in Great Slave Lake.

REPRODUCTION

THE SPAWNING RUN

From May 17 to June 24, 1951, 195 longnose suckers were caught in the Hay River (Table V). The actual spawning act was not observed owing to the extreme turbidity of the water. From May 29 to June 4, the majority of the females examined were latent. After June 6, the percentage of latent females was low, and none were found after June 17. Females in spawning condition were taken up to June 21. Thirty-eight females were in spent condition, being caught from June 2 to 24. The majority of the males were in spent condition. Only 3 males in spawning condition were observed, on June 11 to 13. Suckers were examined between June 12 to 17 from nets set in the lake. They consisted of 1 latent and 15 spent females and 2 spent males. Mr Camsell fished his net

(No. 1) all summer. After July 4, he caught only occasionally a longnose sucker, indicating that they do not usually frequent the river in the summer months.

In the spawning run, females outnumbered the males 104 to 10, a ratio of 10:1. The sex ratio at other times, excluding immature fish, was 2.5:1 (485 females to 196 males).

Surface water temperatures were recorded four times. On June 6 and 7 it was 54°F (12°C) and by June 11 had risen to 59°F (15°C). On June 18, the temperature was 60°F (15.6°C) and by this time suckers caught in the river and

TABLE V. Reproductive condition of longnose suckers caught in the Hay River, 1951.

Date	No. of fish	Females			Males	
		Latent	Spawning	Spent	Spawning	Spent
May						
17–28	69[a]	...	...	...	...	...
29	3	2	1	...	...	...
31	7	7	...	...	...	...
June						
2	5[a]	...	...	...	...	...
4	7	4	3	...	...	...
6	8	3	2	2	...	1
7	7	2	4	1	...	...
8	3	1	1	1	...	...
9	8	1	4	2	...	1
10	9	1	7	1	...	...
11	9	3	4	1	1	...
12	5	1	1	1	1	1
13	7	3	1	2	1	...
14	11	1	5	5	...	...
15	3	1	1	1	...	...
17	12	1	...	9	...	2
18	3[a]	...	...	...	...	...
21	4	...	1	3	...	...
22	4	...	...	3	...	1
23	4[a]	...	...	...	...	...
24	7	...	...	6	...	1
Total	195	31	35	38	3	7

[a]Not examined for sex condition.

in the lake (June 12–17) were in spent condition. This suggests that the spawning run was over and the fish were returning to the lake. Thus, spawning appeared to take place in the Hay River in 1951 after break-up in May to June 15, when the surface water temperature did not exceed 59°F (15°C).

AGE OF SUCKERS IN SPAWNING RUN

The age of 10 males and 87 females was determined. Five females were 9 years old; none were younger. The youngest male was 10 years old. The greatest number of fish (38%) were in the 11 year-old group. The oldest fish

taken were a male and a female, both 15 years old. However, older females, containing large quantities of eggs, were caught later in the summer. These data indicate that the first spawning run is made at age 9. It was seen (Table IV) that fish less than 7 years of age were regarded as immature.

Egg Production

Ovaries were removed from 8 females in spawning condition and the egg counts shown in Table VI were ascertained by a volumetric method. The margin of error was found to be 2% by counting one set of eggs, after first determining the number volumetrically. The actual count was 37,312; the volumetric estimate was 38,195. The counts ranged between 17 and 60 thousand eggs, with an average of 35 thousand. Correlation may exist between age, length, weight and egg number, but the sample was too small to demonstrate a relationship.

Table VI. Egg counts of eight longnose suckers from the Hay River, 1951.

Age	Fork length	Weight		Eggs
	mm	*grams*	*lb*	*no.*
9	450	1090	2.4	17,525
10	490	1590	3.5	38,104
10	526	1950	4.3	60,307
11	465	1540	3.4	38,746
11	505	1630	3.6	20,817
12	505	1590	3.5	24,795
13	568	2040	4.5	42,432
14	523	1540	3.4	37,312

Eggs from ovaries in spawning condition were 3.0 mm in diameter and were invested with a thin gelatinous coat. Eggs from latent ovaries were 1.5 mm in diameter and lacked the gelatinous coat. They appeared to be in a state of early maturation, but not likely to be spawned during the season under study, even though from fish taken in the spawning run. This suggests that the longnose sucker in Great Slave Lake does not spawn every year.

Fingerlings in Seine Hauls

In conjunction with the spawning study, two seine hauls were made in the Hay River, one-half mile from the mouth, on August 15, 1951. The 338 small fish caught consisted of 7 walleye, *Stizostedion vitreum*, 30 spottail shiner, *Notropis hudsonius*, and 301 longnose suckers. The average length of the suckers was 50 mm. The smallest was 33 mm and it had acquired scales consisting of the focus and 2 or 3 circuli. The largest was 66 mm and was also in its first season, although the scales had formed more circuli.

In 1950, seine hauls had been made in the same area on August 22, 27 and 29. Twenty-three longnose suckers, ranging in length from 38 to 80 mm, were caught. All were in their first summer.

SUMMARY AND DISCUSSION

The average rate of growth of the longnose sucker in Great Slave Lake, determined from this study, confirms the results reported by Rawson (1951). The rate of growth was greater in the suckers taken along the south shore, where conditions appear to be more favourable, than in the northern areas.

Rawson (1951) indicated that growth in Great Slave Lake is almost identical with that in Lake Minnewanka, Alberta, and very much faster than in Pyramid Lake, Alberta. It is considerably slower than in Yellowstone Lake, Wyoming (Brown and Graham, 1954), and in part of the Montana portion of the Missouri River (Kathrein, 1951).

Males and females increased in length and weight at the same rate. Females lived longer and grew heavier, as Rawson and Elsey (1950) also found in Pyramid Lake. Brown and Graham (1954) found that males grew more slowly than females in Yellowstone Lake.

The longnose sucker grows considerably larger and lives longer in Great Slave Lake than in other waters. The largest caught, a female, was 642 mm long, weighed 7.3 lb and was 19 years old. This is the largest that has been caught in the Lake and is the North American record (Keleher, 1961). The oldest fish reported for other waters have been 8 years for Yellowstone Lake (Brown and Graham, 1954) and the Missouri River (Kathrein, 1951).

While the date of spawning in Great Slave Lake may differ from that found elsewhere, the water temperature range is similar. Dymond (1926) stated that spawning in Lake Nipigon, Ontario, usually occurs in late May or early June. In Pyramid Lake (Rawson and Elsey, 1950), it began about June 10 and was usually completed by July 1. Streams and certain shallow parts of that lake were utilized. Suckers moved into the streams when the temperatures were 52–57°F (11–14°C), but remained in the lake when the inflowing water was at 48°F (9°C) or lower. Brown and Graham (1954) found spawning in late June in Yellowstone Lake, the run continuing through most of July. Sucker movement was influenced by water temperature changes. Pronounced changes in temperature were associated with similar changes in the numbers of fish entering the traps. The greatest numbers were taken when the temperature was in the range 50–59°F (10–15°C).

The sex ratio observed in the Hay River spawning run was 10 females to 1 male. The small number of males suggests that the run was almost over and just late spawners, mostly females, were caught. It is known that the males of many fishes precede the females on the spawning grounds. Out of 97 spawning-run suckers, 83% of the females and 90% of the males were from age groups 10 to 12. Both sexes were considered to be sexually mature at 7 years, but no specimens younger than 9 were found in the spawning run. Some males and females were sexually mature at age 4 and spawned in their 5th summer in Pyramid Lake (Rawson and Elsey, 1950), and all individuals were mature at age 6. Brown and Graham (1954) found that males in Yellowstone Lake rarely spawn before they are 4 years old and females before they are 5 years old. Most of the males were age 5, while the majority of the females were age 6.

Egg size differences of fish captured in the spawning run at Hay River suggest that mature longnose suckers do not spawn each season. The suspicion that some fishes may not spawn annually in northern waters apparently was indicated first by Miller and Kennedy (1948). Later, several other species were believed to spawn at longer than yearly intervals (see Kennedy, 1953).

The longnose sucker spawns in the Hay River and probably other streams entering Great Slave Lake. The fry and fingerlings spend at least their first summer in the river; samples taken August 15 averaged 50 mm (range 33–66 mm), and all had scales. In Yellowstone Lake streams, Brown and Graham (1954) found fry and fingerlings ranging in total length from 11 to 15 mm in July, 19 to 30 mm in September, and 25 to 38 mm in October. The smallest fish to have scales was 38 mm. They postulated that the Yellowstone Lake suckers are without scales during their first winter.

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Glycogen Stores in Trout Tissues Before and After Stream Planting[1]

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ABSTRACT

Changes in the glycogen reserves of epaxial and heart muscle of trout were followed after stream planting. Muscle glycogen recovered quickly in large fish; more slowly in smaller ones, and was related to earlier reported changes in liver glycogen and blood lactic acid. Heart glycogen increased initially, but fell again shortly after feeding became stabilized. Muscle glycogen reserves of wild trout were lower in the presence of hatchery fish than in their absence. A depletion of some metabolite, such as glycogen, in conjunction with an increased body demand due to raised basal metabolism was suggested as a factor in delayed mortality.

INTRODUCTION

"Delayed" mortality of planted hatchery fish has been observed frequently, but has not been fully explained. On the basis of changes in blood lactic acid concentrations shortly after planting, Miller (1958) postulated the depletion of a metabolite and acidosis as causes of death. Miller *et al.* (1959) found a close relation between diet and glycogen stores and suggested that mortality may be due to a depletion of these reserves.

This study has been designed to test the above considerations. To aid in interpreting field data, further feeding and starvation tests were carried out.

Experimental Trout

Recently-hatched rainbow trout, *Salmo gairdneri*, were divided into 2 groups — each with fingerlings averaging 1.9 g. One lot was fed the Clark's dry rations (described by Miller *et al.*, 1959), while the second was given another pelleted food, the Encore diet.[3] Both groups were maintained in large circular tanks. The water temperature was about 4°C; the water velocity averaged about 1 ft/sec (0.3 m/sec). The water was saturated with oxygen. These

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[3]According to the manufacturer's label, the Encore diet consists of wheat middlings, Soy bean meal, fish meal, meat scraps, milk powder, corn distillers solubles, Brewer's yeast, fortified fish oil, and iodized salt. Crude analysis yields: 36% protein, 2.15% crude fiber, 0.6% ash.

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conditions were maintained for 7 months. At this time the experimental fish were similar:

	Encore diet	*Clark's diet*
Average weight	21.2 g	21.8 g
Mortality	6.7 %	5.4 %
Food conversion factor[4]	2.3	2.0

The experimental trout used in the field tests were from the stock described by Miller *et al.* (1959). Two dietary lots were used: Clark-fed fish, with an average weight of 96 g, and trout fed on fresh beef liver, with an average weight of 66 g. The wild stock, *Salmo clarki* had an average weight of 53 g.

Laboratory Methods

To determine the effects of starvation, 30 trout of each diet were isolated in long narrow troughs, and left undisturbed, except during tissue sampling, for 2 weeks.

To determine the effects of heavy feeding, normal Clark-fed fish were divided into 2 lots of 50. One group was fed the Encore diet at a rate double that recommended by the dealers; the second was fed, at the same rate, an arbitrarily adopted 10:3 mixture of the Encore food and clinical grade glucose. The feeding lasted 7 days.

Samples of liver, epaxial muscle, and whole hearts were placed directly into tubes containing 30% potassium hydroxide. Glycogen was assayed by the method of Montgomery (1957).

Field Methods

Field tests were carried out at George Creek, west of Turner Valley, Alberta (Miller, 1958; Hochachka, 1961). Hatchery fish were planted into 3 experimental zones. Mortality was checked every few days throughout the experiment. Tissue sampling was carried out at the stream and analysis methods were the same as above described. Stomachs of dead fish were collected on the stream and examined in the laboratory.

A fourth zone was set aside for field-testing the effects of heavy feeding of the Encore diet and the Encore-glucose mixture.

Although the population density to which the experimental fish were being subjected varied in the different stream sections (Hochachka, 1961), it did not markedly affect the parameters discussed in this paper. Consequently, the data are grouped together according to diet rather than steam section.

RESULTS OF LABORATORY TESTS

Normal Glycogen Levels

Levels of liver, cardiac, and muscle glycogen in unexercised trout fed on different diets are recorded in Table I. The data show the Clark's pellets provide the fish with the highest glycogen stores; fresh beef liver is most inadequate (Miller *et al.*, 1959); and the Encore rations fall between the other two diets.

[4]Pounds of food used divided by pounds of fish produced.

TABLE I. Glycogen reserves of normally-fed, heavily-fed, and starved hatchery *Salmo gairdneri*. Heavy feeding of the Encore pellets or Encore-glucose mixture to trout previously fed Clark's diet lasted for 7 days. Values for liver-fed trout are from Miller *et al.* (1959). Glycogen is expressed in grams per 100 g tissue, wet weight, with standard errors of the means.

(Numbers in brackets refer to numbers of fish sampled.)

Lot	Normal feeding	Heavy feeding		Starvation	
		Encore diet	Encore-glucose	7 days	14 days
A. Liver glycogen					
Clark-fed	4.132±0.325 (10)	10.033±0.518 (5)	16.345±1.558 (5)	1.314±0.386 (5)	0.933±0.146 (5)
Encore-fed	3.308±0.285 (10)	....	....	1.659±0.419 (5)	1.193±0.214 (5)
Liver-fed	2.59±0.28 (20)	....	....	....	....
B. Muscle glycogen					
Clark-fed	0.174±0.012 (10)	1.441±0.055 (5)	1.592±0.130 (5)	0.151±0.023 (5)	0.112±0.029 (5)
Encore-fed	0.146±0.009 (10)	....	....	0.149±0.012 (5)	0.098±0.007 (4)
Liver-fed	0.118±0.021 (2)	....	....	....	....
C. Heart glycogen					
Clark-fed	0.541±0.047 (10)	1.403±0.067 (5)	1.460±0.095 (5)	0.778±0.102 (5)	0.350±0.024 (5)
Encore-fed	0.440±0.052 (10)	....	....	0.796±0.176 (5)	0.339±0.056 (5)

Heavy Carbohydrate Feeding

Heavy feeding of the Encore diet produced 2– to 2.5–fold increases in liver glycogen deposits ($P<0.01$), while feeding the Encore-glucose mixture caused about 4–fold increases (Table I).

Glycogen in the epaxial muscle was even more profoundly influenced by heavy feeding of the Encore diet (Table I); these deposits were 8–9 times higher than normal. The glucose addition produced only a small additional increase, probably non-significant.

Heart glycogen also rose with heavy feeding of Encore diet. As with epaxial tissue, dietary glucose raised these levels slightly higher, but this increase was not significant. Perhaps an upper limit to the possible concentration of glycogen in these tissues had been approached.

Starvation

As expected, starvation led to a fall in liver glycogen. Resistance to this depletion was not affect by the diet. Table I shows that 7 days of starving caused 65–70% decreases in the liver concentration of glycogen in both Clark-fed and Encore-fed groups, but another week without food did not significantly reduce the already-low deposits.

Both Clark-fed and Encore-fed fish maintained their muscle glycogen stores even after 14 days of starvation.

Starvation influenced the glycogen deposits in the heart in an interesting fashion. As indicated in Table I, fasting for 7 days increased these stores by about 45%. However, an additional 7 fasting days lowered these levels to somewhat below normal.

RESULTS OF FIELD TESTS

Mortality of Hatchery Rainbow Trout following Stream Planting

The data dealing with relative mortality of the two lots tested in the field are summarized in Table II. The striking fact is the wide difference in survival between the large Clark-fed trout and the smaller liver-fed ones; most of the mortality occurred in the latter group. However, the time sequence of mortality was similar in both groups, 70% of that observed occurring within the first 8 days.

Mortality was low in the heavily-fed fish: 2 out of 50 fish that had been fed the glucose-Encore mixture were found dead within 2 weeks after stream planting; only 1 out of the 50 fish that had been fed Encore pellets at twice the normal rates was found dead.

No dead native trout (*S. clarki*) were found during the field experiment.

Weight losses of dying fish were similar to the weight loss of surviving trout (Hochachka, 1961).

The stomachs of all dead trout discovered, about 30 in number, were completely empty. The consistency of this finding was striking. Occasionally, but not generally, the stomachs of surviving hatchery trout taken during sampling periods in the first weeks after planting also were empty.

Muscle Glycogen Recovery after Planting

Data dealing with glycogen reserves in the muscle of hatchery and wild trout are recorded in Table III. Although Clark-fed trout tended to have more glycogen in the epaxial tissue than liver-fed fish at the beginning of the experiment (i.e. after 60 miles transportation, as described by Hochachka, 1961), the difference was not statistically significant. However, the rate of recovery was faster in Clark-fed fish, so that by 1 week after planting, this group had significantly higher levels than liver-fed fish ($P=0.01$), and this advantage was maintained until the fourth week.

Both Clark-fed and liver-fed rainbow trout had less glycogen in the epaxial mass than the smaller wild *Salmo clarki* through the duration of the experiment. It is notable, however, that the muscle glycogen reserves of resident cutthroat trout were lower *after planting the hatchery fish* than before ($0.01>P>0.05$).

The muscle glycogen of fish that were fed the Encore diet at twice the normal rate, or the Encore-glucose mixture, was not extensively depleted during transportation to the stream. Moreover, the stores of glycogen in the epaxial tissue of these trout were higher than in normally-treated hatchery stock for at least 2 weeks after planting (Table III).

Table II. Mortality and weight loss of hatchery *Salmo gairdneri* after planting. Total mortality includes dead fish found during the experiment and at its termination. Weight data, expressed as percentage decrease from planting weight, were obtained from freshly dead fish. (Numbers in brackets refer to numbers of fish sampled.)

Lot	Total mortality	Weight decrease
Clark-fed	10% (14)	6.6% (7)
Liver-fed	20% (28)	7.6% (26)

Changes in Cardiac Glycogen after Planting

Data dealing with glycogen in the heart muscle of the various trout groups are tabulated in Table IV. On arrival at the stream, the Clark-fed and liver-fed groups had above-normal concentrations of glycogen in the heart muscle. These fish showed further increases in cardiac glycogen during the first week after planting, but a return to normal conditions occurred in subsequent samples. By 4 weeks after planting, the levels were again lower than those seen in the resident *Salmo clarki*.

Trout that had been fed a glucose-enhanced mixture and those that were simply heavily fed the Encore food showed the highest concentrations of glycogen in heart tissue. In these groups, there were no initial increases. Rather, the heart stores of glycogen were gradually reduced approximately to the levels seen in the wild stock.

There were no significant differences between resident *S. clarki* before or after planting of the hatchery fish.

Changes in Liver Glycogen after Planting

The course of variation in the concentration of glycogen in the liver of stream-planted hatchery fish has been discussed elsewhere (Hochachka, 1961) and details will not be repeated here. However, it should be noted that the effects of heavy feeding on glycogen in the liver were similar to those for heart tissue. By two weeks after planting, the initially high levels were reduced to the same concentration as in the liver of normally-treated fish—about 2.5 g per 100 g liver.

DISCUSSION

Hatchery Fish Mortality after Planting

The patterns of mortality recorded in this study are similar to those observed by other workers. Thus, Miller (1951) found 40% mortality when the density of the hatchery trout at the time of planting was about 160–200 fish per 300 yards of stream. In addition, he found a higher proportion of large trout surviving than of smaller, younger ones — an observation in excellent agreement with the lesser mortality of the larger Clark-fed trout that we found in this study. Needham and Slater (1943), using fairly small trout and planting at a density of about 500 fish per 300 yards, reported 44% mortality, and analogous data have been presented by others (Miller, 1958).

Tissue Glycogen

Many factors are known to influence glycogen deposits in the liver. Plattner *et al.* (1956) found that magnesium ions *in vivo* promote glycogen synthesis. Ascorbic acid also is an influencing factor (Nadel *et al.*, 1955). Thiamine is known to increase glycogen storage in mammals and fish (Siliprandi and Siliprandi, 1951; Harper, 1942). In addition, alloxan was found to stop glycogenolysis in the bullfrog (Goldner and Jauregui, 1953). Experiments determining the dietary value, in terms of fish survival, of any of these factors would be welcomed by the fish manager.

Although in this study heavy feeding apparently enhanced survival, high-carbohydrate diets may be associated with increasing mortality, due either to high deposits of glycogen in the liver (Phillips *et al.*, 1948), or to increased lactic acid production during activity (Parker *et al.*, 1959). However, in the stream, the abnormally high stores of glycogen were quickly reduced to the same levels as in normal fish, thus alleviating any danger. The important point is that the heavily-fed trout could reach this normal level passively, while the others had to do its actively (i.e. by feeding). This situation may enable the heavily-fed trout to expend more energy in adjusting to their new environment, less in maintaining fuel for activity. That is, heavy feeding may provide the fish with an energy advantage over non-treated ones, and herein may lie the basis for greater survival.

Using blood lactic acid as a measure of activity, Miller (1958) found that this acid, although high at planting, dropped to quite low levels for a period of several days after the plant. Levels were again very much above normal after

TABLE III. Muscle glycogen of wild *Salmo clarki* and hatchery *Salmo gairdneri* before and after the latter were planted in a mountain stream. Fish were sampled (1) at the hatchery before being transported to the stream, (2) on arrival at the stream, and (3) at weekly intervals after planting. Values for wild cutthroat trout are lumped into those collected during 4 weeks prior to the experiment and those collected during the experiment. Values marked with an asterisk are from Miller *et al.* (1959). Glycogen is in grams per 100 g tissue, with standard errors. (Numbers in brackets refer to the number of fish sampled.)

Lot	Before Planting	At Planting	Days after planting			
			6–8	13–15	20–22	27–29
Wild	0.329±0.036 (19)	....	....	....	....	0.234±0.014 (20)
Clark-fed	0.178*±0.079 (20)	0.114±0.012 (5)	0.135±0.010 (13)	0.155±0.011 (11)	0.154±0.013 (11)	0.133±0.006 (12)
Liver-fed	0.118*±0.021 (20)	0.089±0.012 (5)	0.073±0.007 (14)	0.100±0.007 (11)	0.111±0.065 (11)	0.128±0.011 (12)
Encore-glucose mixture	1.592±0.130 (5)	1.511±0.097 (3)	0.341±0.064 (4)	0.245±0.023 (4)	....	....
Encore-fed at doubled rates	1.441±0.055 (5)	1.083±0.153 (3)	0.296±0.041 (4)	0.184±0.043 (4)	....	....

TABLE IV. Heart glycogen of wild *Salmo clarki* and hatchery *Salmo gairdneri* before and after the former were planted in a mountain stream. Details and units as in Table III.

Lot	Before planting	At planting	Days after planting			
			6–8	13–15	20–22	27–29
Wild	0.852±0.071 (22)	....	....	....	....	0.970±0.084 (19)
Clark-fed	0.541±0.047 (10)	0.766±0.159 (5)	1.180±0.112 (13)	0.626±0.097 (11)	0.673±0.086 (11)	0.694±0.016 (13)
Liver-fed	....	0.346±0.096 (5)	0.727±0.113 (14)	0.647±0.074 (11)	0.641±0.065 (11)	0.719±0.078 (12)
Encore-glucose mixture	1.466±0.095 (5)	1.561±0.115 (3)	1.104±0.093 (4)	1.013±0.120 (4)	....	....
Encore-fed at doubled rates	1.403±0.067 (5)	1.366±0.084 (3)	1.161±0.097 (4)	1.071±0.207 (4)	....	....

about 10 days. To him this suggested the immediate exhaustion of some metabolite which was involved in lactate production, and which was replaced when feeding activity increased. Table II shows that in liver-fed trout muscle glycogen could perhaps be the compound concerned, for the levels were well below normal for at least one week after planting. By two weeks, an apparent restoration pattern began and showed clearly by 4 weeks. This time sequence dit not hold true for the Clark-fed lot, but Miller used liver-fed fish.

Cardiac glycogen fluctuations are not well understood. Russel and Bloom (1955) suggested that the action of the growth hormone is enhanced during fasting, causing the oft-observed increase in glycogen of the heart. Presumably the same mechanism is at least partly responsible for the initial rise in our fasting and field experiments, although a greater emphasis on fatty acid metabolism during starvation might produce the same effect (Shipp *et al.*, 1961).

Lactic acid in the blood could lead to glycogen deposition in the heart. However, McGinty (1931) found that in dogs, at any rate, cardiac absorption of lactic acid was independent of the concentration in the blood. This is not known for fish. Since in our experiments blood lactate was low at the time of maximum glycogen deposition in the heart (Miller, 1958), this mechanism of heart glycogen deposition may not be too important.

Bloom and Russel (1955) showed that glycogen in the heart was increased after treatment with epinephrine or norepinephrine, while Christian (1959) has suggested an interplay between population density and adrenal function. If this mechanism holds for trout, then it too could be contributing to the increase in heart glycogen that was seen shortly after planting, when competitive conditions were most severe.

Finally, the expenditure of heart energy reserves during active metabolism (e.g. feeding, maintaining stream position, etc.) could account for the lower levelling-off concentration of glycogen in the hearts of hatchery trout relative to wild stock, and of liver-fed ones relative to the Clark-fed fish. Presumably the smaller, liver-fed, trout would be subjected to harsher conditions (Miller, 1958; Hochachka, 1961).

Cause of Hatchery Trout Mortality following Planting

The cause of "delayed mortality" has been obscure. Horton (1956) associated such death with temperature and aeration during transportation. Black's (1956) study of blood lactate during transportation seemed to suggest that fish were not succumbing to this metabolite (Miller, 1958). In this connection, some unpublished experiments at the Alberta Biological Station in 1958 showed that moribund trout had abnormally high blood lactic acid concentrations (R. B. Miller, personal communication). This was interpreted as evidence for Miller's (1958) hypothesis, that depletion of some essential metabolite(s) led to death by acidosis. However these blood samples were taken from fish which, having been washed against the fences, were struggling in their death throes. Under such conditions, the accumulation of detrimental acid products would be inevitable and expected. The weakness which brought them near the fence in the first place *might* have had other symptoms.

During the present experiment, trout which had been washed very near to the fish fences were infrequently sampled, in order to avoid influencing the mortality picture. Those that were taken showed liver and muscle levels of glycogen easily within the range observed in the laboratory fasting experiments, but heart reserves were substantially higher (about 1.6–2.0 g% as compared to *fasting* levels of about 0.8 g%). Hence some other factor, probably *adrenaline*, had to be involved. If an adrenaline response to competition is indeed concerned, as in mammals (Christian, 1959), then an important consequence would be a *raised metabolic rate.*

It is also noteworthy that the stomachs of all the dead fish found were empty. This has been observed in the past by Miller and his co-workers, but since weight losses of dying and surviving trout were similar and death occurred so soon after planting, the implications of starvation were not fully appreciated.

Without minimizing the effects of transportation methods, temperature and high tissue acidity, we suggest that depletion of some essential metabolite(s), such as glycogen, *in conjunction with an increased body demand as a result of increased standard metabolism*, may be instrumental in delayed mortality. A similar principle has been enunciated by Brett (1957) in his discussion of metabolic load and salmon swimming capacity. Both ideas are in harmony with the role of competition in hatchery fish survival; indeed, they point to a mechanism for that role.

SUMMARY

1. A study of glycogen reserves in tissues of hatchery rainbow trout and wild cutthroat trout was made. These reserves were again shown to be influenced by nutrition.
2. After planting, more small hatchery fish died than large ones; those fed temporarily on high carbohydrate diets survived best.
3. Muscle glycogen was reduced to low levels during transportation, while heart levels of glycogen tended to rise.
4. The larger hatchery fish recovered muscle glycogen stores more rapidly and maintained higher levels throughout the experiment.
5. Glycogen deposits in the muscle of the smaller, wild trout were higher than in normally-fed hatchery fish, but were lower in the presence than in the absence of the introduced groups.
6. Glycogen in heart tissue increased initially after planting, probably because of fasting and adrenaline effects, but fell after feeding began.
7. A depletion of some metabolite, like glycogen, in conjunction with increased body demands for it as a result of a higher basal metabolism, is suggested as contributing to delayed mortality after planting.

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Preliminary Studies on the Visible Migrations of Adult Salmon[1, 2]

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ABSTRACT

Techniques have been developed for observing and recording the behaviour of migrating adult salmon. Daytime movement through slow water (less than 5 ft/sec (1.5 m/sec)) is by steady swimming in schools. Such steady swimming is interrupted with resting periods at velocities between 3 and 5 ft/sec (1.0–1.5 m/sec) but can be sustained over long periods at velocities less than 3 ft/sec (1 m/sec). Movement through slow water in the Somass River system normally occurs along the line of the deepest channel, wherever this is well defined. Movement through rapids (velocities more than 5 ft/sec or 1.5 m/sec) is by darting interspersed with holding, salmon moving individually rather than in schools. Migration through pools, and through other obstructions such as fishways shows diurnal rhythms, modifications of which are associated with numbers of salmon moving, the time within the migratory season, and the species concerned. Nocturnal migration occurs.

Entry of salmon into rivers during the migratory season occurs at intervals, the initiating stimulus for which is frequently related to the passage of atmospheric warm fronts over the river estuary.

Techniques for field behaviour studies of salmon migration have a potential for management in that it is possible to undertake such studies in areas scheduled for industrial development and to utilize the revealed spatial and temporal migration patterns in the design of fish diversion facilities.

INTRODUCTION

An investigation of the ecology of salmon migrations in rivers has been in progress at the Biological Station, Nanaimo, British Columbia, for four years. The immediate objective is to describe the visible migrations of adult salmon. Such information, plus the development of techniques for making the migration visible, is useful to biologists and engineers concerned with predicting and anticipating the effects of industrial water-use developments on salmon migrations. The data also have fundamental scientific value in the understanding of animal migrations and orientating mechanisms. This preliminary report is a review of concepts and progress utilizing observations on sockeye salmon (*Oncorhynchus nerka*) and coho (*O. kisutch*) in the Somass River system on Vancouver Island, British Columbia.

There have been two basic principles followed in these studies. The first consists of looking for evidence for the many biological phenomena known to

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[2]Paper No. 5 concerning the physiology and behaviour of salmonid fishes from the Fisheries Research Board of Canada Biological Station, Nanaimo, B.C.

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affect animal migrations. These include diurnal, lunar and seasonal rhythms of activity, the effects of atmospheric and water conditions, topography, social effects of crowding, relationships between learned and instinctive behaviour, etc.

The second principle concerns working techniques. Ornithological studies have shown the value of maintaining observation posts regularly throughout the migration season, which practice has been followed here. In this investigation, some of the observation posts are underwater and some above the surface. They are occupied for up to 24 hours at a time, steadily or intermittently; and at them are recorded the occurrence of various activities of migrants, e.g., routes selected, swimming speeds, numbers passing, types of progression (steady swimming or darting), social behaviour (biting or chasing, fin signalling, lateral display, etc.), and a number of other actions (yawning, chafing, jumping, etc.), some of which are common, others rarely seen.

For descriptive field studies of animal behaviour it is necessary to have effective observation and recording techniques. These were not available for aquatic animals at the time this study was started in 1957, and the first three years have been spent largely developing methods: first, a system for breaking down salmon migratory activities into recordable categories; second, the use of Scuba diving for underwater observations; and third, the use of still and ciné-photography from both above surface and underwater as recording tools. A paper on diving and photography as used in these studies has been prepared (Ellis, in press). A movie demonstrating some migratory activities of salmon has been assembled from the underwater test footage. The investigation is now in a position to observe and record salmon behaviour in many previously uninvestigatable habitats, e.g., waterfall pools, the eddies of rapids, and in general under moderately turbulent water. There are still some habitats presenting technical problems, such as strong turbulent water, and, at the other extreme, calm open water of the pelagic environment where salmon keep well away from divers.

The main working area of the investigation, the Somass River and its larger tributaries (Fig. 1) has discharges fluctuating at different times and in different salmon branches from 100–10,000 ft^3/sec. Each year there is a migration of up to 100,000 salmon of all 5 species of *Oncorhynchus* into the sytem. The major tributaries consist essentially of a mixture of three types of habitat: river pools rarely more than 50 feet (15 m) deep and usually much less; obstructions in the form of rapids, falls and fishways; and unobstructed sections usually with low current velocities and well defined deepest channels rarely more than 10 feet (3 m) deep. The main reasons for selecting this system were its clear water permitting good observation of salmon behaviour, and the ease of access by truck carrying recording gear to many points of observation.

RESULTS

Results are accumulating from the many observation posts occupied either regularly or occasionally. A selection of three sets of data will be presented to illustrate the nature of the research, the results obtainable, and general conclusions to date.

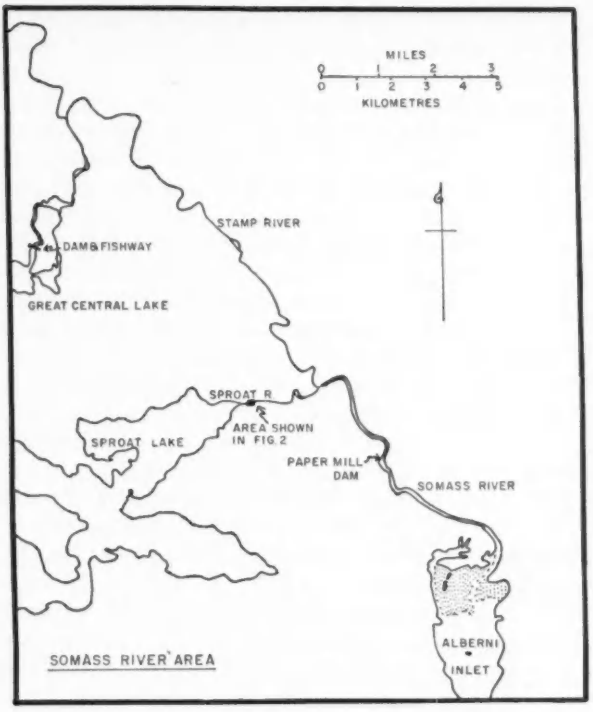

FIG. 1. Map of the Somass River area showing the principal observation points.

ROUTE SELECTION AND MIGRATION PATTERNS IN THE UPPER SPROAT RIVER

Figure 2 shows the plan and four cross-sections of part of the upper Sproat River (Fig. 1). The route of adult sockeye and coho from late June to early September is indicated by the arrows. Almost 100% dart up the rapids into Holding Place 1 (HP 1) and pause there. They then swim steadily along the deepest channel (cross-section GH) close to the bottom through Holding Places 3 and 4. The pool above Holding Place 4 is a region of irregular depth (cross-section EF) and routes through it are variable. At the upper end of the pool, routes converge again to the deepest channel (cross-section CD) until the shallows are reached. Here, the deepest channel leads into a blind alley (cross-section AB), and salmon must deliberately leave it in order to pass over the shallows. Ascending schools on their first attempt, usually consisting of few (1–10) fish, take devious routes below the shallows, finally enter the deepest channel blind alley, turn, and retreat to the pool.

As a result of these returns and the continual arrival of more fish from downriver, numbers during intensive runs may build up in the pool to 100 or

even more fish. The schools in the pool may either hold for long periods at Holding Place 5 with some jumping, or may wander up and down the pool by steady swimming with many individuals jumping. Downriver wandering is close to the surface, and usually terminates before Holding Place 3 in shallowing water. Turning at this lower end of the pool is associated with descent to the bottom, and subsequent upriver movement which may take the school back up to the shallows. Such returning schools have more success in crossing than schools on their first attempt. After some indecisive movements below the shallows, a few fish dart over and the rest follow in the same manner.

On their first ascent of this area, from rapids through the pool to the shallows, salmon follow the line of the deepest channel wherever it is well-defined. They are apparently guided by bottom topography. If misled by this, as in the blind-alley situation, on a subsequent ascent they will eventually take the correct route. They appear, then, to have changed their orientation cue to, for instance, fastest current coming over the shallows. This area is one of the several where our observations suggest the possibility of position learning and habitat recognition by salmon while migrating.

Salmon passing, by means of steady swimming, from the rapids into the pool through HP 1, HP 3 and HP 4 were timed with a stop-watch in 1960. Migration speeds, water velocities and calculated swimming speeds are shown in

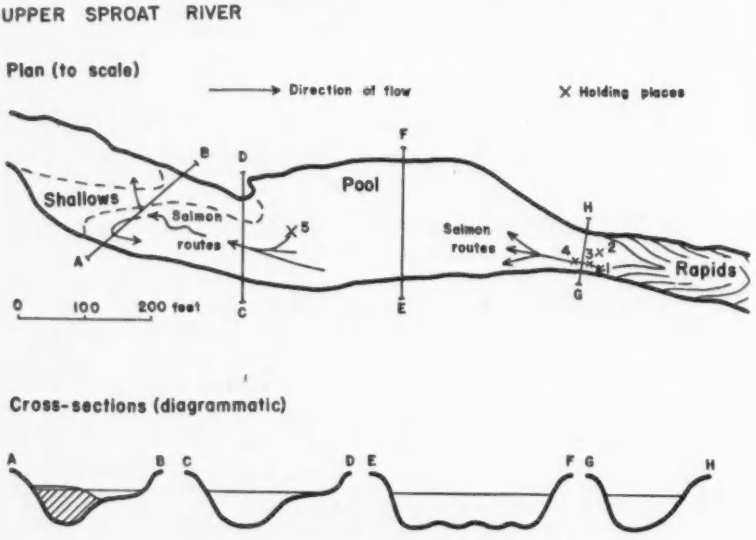

FIG. 2. Scale plan and diagrammatic cross-sections of a part of the upper Sproat River. Migrating adult salmon follow distinct routes along the well-defined deepest channels shown in sections CD and GH. Routes are variable in the pool (section EF) with no clearly defined deepest channel. Upriver movement below section AB is variable and may lead salmon into the deepest channel backwater or out of the deepest channel over the shallows. The diagonally shaded area in section AB represents the deepest channel blind alley.

Table I. In June and early July with surface water velocities averaging 3 ft/sec (1 m/sec) or more, steady swimming speeds[3] of the fish were even higher, from 4 to 5.5 ft/sec (1.2–1.7 m/sec). During this period all ascending salmon held at HP 1 and from 50% to 80% at HP 3 and HP 4. Many salmon arrived at HP 1 in a grouped, but not a schooling, fashion and reformed into schools before leaving HP 4. Grouping and schooling are used here descriptively. Salmon groups are called schools if the individuals appear to be orientating to one another. This is most convincingly shown when two or more salmon mill, i.e. circle around each other, a fairly common activity in river pools.

From late July to early September, water velocities between HP 1 and HP 4 had dropped (through reduced discharge) to about 2 ft/sec (0.6 m/sec). Steady swimming speeds of sockeye over the area had also dropped to about 3 ft/sec (1 m/sec). No fish held at either HP 3 or HP 4, although all continued to hold at HP 1 after passing up the faster water of the rapids. Furthermore, in August and September, most salmon were passing through the entire area in schools, including the ascent of the rapids.

The observations suggest that there are two critical water velocities for adult migrants. One is at about 3 ft/sec (1 m/sec). Below this level, adult salmon can maintain a steady swimming pace without need for resting periods. The other critical velocity is about 5 ft/sec (1.5 m/sec) or more. Schooling appears to break down at a water velocity in excess of 5 ft/sec (1.5 m/sec), and at that speed also, steady swimming is replaced by darting.

Another point concerning the speed of migration arises from the occurrence of holding at HP 3 and HP 4. Fish which hold may take minutes, occasionally hours, to pass from rapids to pool, whereas non-holding fish cover the same distance in seconds. Although accurate data on holding times have yet to be obtained quite obviously non-holding salmon pass through the area considerably faster than holding salmon. Environmental situations which cause holding, in effect, slow down migration speeds very considerably.

Steady swimming, then, is the means of progression for adult salmon through water velocities less than about 5 ft/sec (1.5 m/sec). According to observations at another locality on the Sproat River, such steady swimming at water velocities less than 3 ft/sec (1 m/sec) can be sustained for at least 300 ft (100 m) and perhaps indefinitely, whereas we have already seen that steady swimming at rates between 3 and 5 ft/sec (1–1.5 m/sec) is interspersed with resting periods, even after short distances of only 20 ft (6 m).

It must be added here, that field data such as these figures for migration speeds, water velocities and swimming speeds are necessarily subject to considerable error. They need to be supplemented by experimental studies to arrive at more accurate figures. Nevertheless, since more extensive date obtained in 1961 support these observations, the principle of two critical water velocities for salmon migration appears to be sound, even if the velocities in relation to salmon size, migratory drive and other factors should be more precisely determined.

[3]Steady swimming is used in this paper to mean a type of progression distinct from darting but implies nothing about the lengths of time for which it is sustained.

TABLE I. Salmon swimming speeds and associated behaviour at Upper Sproat River, 1960.

Date	Species	Holding place 1–3 (21 feet)					Holding plase 3–4 (26 feet)					Occurrence of schooling	
		Number of salmon timed	Migration speed[a]	Water velocity	Steady swimming speed[b]	Proportion holding at HP3	Number of salmon timed	Migration speed[a]	Water velocity	Steady swimming speed[b]	Proportion holding at HP4	On arrival at HP1	On departure from HP4
			ft/sec	*ft/sec*	*ft/sec*	%		*ft/sec*	*ft/sec*	*ft/sec*	%		
June 21	sockeye	41	1.1	4.4	5.5	80	...	...	...	...	...	...	...
22	sockeye	13	1.1	4.4	5.5	80	24	1.1	3.1	4.2	50	no	yes
July 13	sockeye	27	1.0	3.2	4.2	80	19	1.2	2.8	4.0	50	no	yes
28	sockeye	1	0.6	2.2	2.8	0	5	1.8	1.6	3.4	0	...	...
Aug. 15	sockeye and coho	38	1.1	1.8	2.9	0	45	1.8	1.4	3.2	0	yes	yes
Sept. 5–6	coho	10	1.2	1.9	3.1	0	13	2.3	1.5	3.8	0	yes	yes

[a]Observed rate of travel over measured distance.
[b]Sum of migration speed and water velocity.

These results contribute to a growing knowledge about, and interest in, sustainable swimming speeds as opposed to darting speeds (Boyar, 1961; Bainbridge, 1960). They support these recent contributions in showing that sustainable swimming speeds are considerably slower than maximum speeds, which in adult salmon have been variously estimated up to 36 ft/sec (11 m/sec) (Bainbridge, 1958). They suggest, in fact, that sustainable swimming is the main form of progression during salmon migration, and that dart swimming is used under obstructed conditions. (Dart swimming however also is part of the normal escape responses of salmon).

At water velocities greater than 5 ft/sec (1.5 m/sec), the river habitat is that of rapids. Passage through rapids then is by means of darting movements interspersed with holding, with the fish travelling independently rather than in schools.

Holding, however, has more significance than being simply a resting period between bouts of strenuous activity, as in many river pools holding may last for hours or may alternate with leisurely wandering in calm water.

Passage through river pools is now being investigated. Salmon can often be seen holding at the edge of the main current at particular places, but they respond to the presence of divers by wandering movements taking them up and down the pool close to the bottom. This apparently is not normal migratory behaviour, but a weak escape response limited by the dimensions of the pool. Salmon appear to enter and leave pools and other obstructed areas at particular times of day, as is described in the next section.

DIURNAL RHYTHMICITY AT GREAT CENTRAL LAKE FISHWAY

Standardized 8-hour daily counts (starting at dawn) of salmon leaving the fishway at Great Central Lake dam (Fig. 1) in 1959 show that peak movement occurred for limited periods during the day, and that the timing of the peak was variable. Figure 3 shows three characteristic daily time distributions. The 103 daily counts of 1959 have been grouped for convenience into 62 type 1, 32 type 2 and 9 type 3. Type 1 indicates that a wave of salmon passed through the fishway within a few hours of dawn, type 2 that two waves ascended the fishway during the counting period, and type 3 that numbers increased during the afternoon and probably continued after the routine counts had stopped. Sockeye salmon generally, and coho occasionally, had a type 1 distribution. Type 2 distribution included most of the remainder of the sockeye, and about half of the coho. Type 3 distribution was principally shown by late-run coho.

It is possible to test the significance of the differences between hourly proportions by χ^2. Tests were made using early, intermediate and late runs, and low, intermediate and high daily counts for both sockeye and coho. Three significant differences at the 5% level were found. Late-run (August) sockeey were more concentrated around dawn than early-run (June) sockeye. Early-run (August) coho were more concentrated around dawn than late-run (September and October) coho. Small numbers of coho (less than 50/day) were more concentrated around dawn than large numbers (more than 150/day). There

appear to be changes in the timing of salmon passage through the fishway related to time within the migratory season and numbers of fish travelling together, i.e., a crowding effect.

A further meaningful variation in the hourly proportions showed up within the type 1 distribution. The 1959 data produced occasional days with peak passage during the first hour after dawn rather than the second. This suggested some pre-dawn movement through the fishway. Consequently, some night observations were made in 1960, and then extensive night work was undertaken in 1961. At Central Lake dam night observations were made as salmon passed, silhouetted, over a sunken white board at the mouth of the fishway. A similar technique was used where possible elsewhere; failing that, flashlights were used by both above-surface and underwater observers.

The 1961 data have yet to be analysed in detail, but they show unequivocally that nocturnal migration is an important feature of sockeye migration in the Somass system. At Central Lake dam, for instance, numbers passing out of the fishway between dusk and dawn at times equalled numbers leaving during the post-dawn movement. It was noticeable at the dam that night-movers left the fishway singly, whereas day-movers left in schools.

These observations at Central Lake fishway are one of a number which show the existence of 24-hour behavioural rhythms within salmon migration. These rhythms appear to be modified by a variety of factors including at least the numbers of fish moving (a crowding effect), the time within the migratory season, and species differences.

SALMON ENTRY INTO THE SOMASS RIVER

At the upper limit of tidal water, in a pool below a rapids known locally as Paper Mill dam (PMD) (Fig. 1), it is possible to make standardized daily 1-hour counts of numbers of salmon jumps starting at dawn. These cover a portion of the daily peak jumping period, i.e. jumping shows as 24-hour rhythm, peaking soon after dawn. Daily fluctuations in such jump counts are shown in Fig. 4 for the period of the late sockeye run in 1959. Periods of much jumping fall into groups lasting several days. The studies on the Somass River watershed have come to rely on the daily PMD jump counts, as they indicate whether sufficient salmon are moving to justify making behaviour observations upriver. For the jump counts to be as consistently reliable indicators of migration as they are, their daily fluctuations must be related to fluctuations in numbers of salmon ascending the river. This can be checked in a more rigorous fashion by correlating jump counts against numbers of fish passing through Great Central Lake fishway about 15 miles upriver, but this analysis will not be presented until more data have been gathered.

Having established that daily fluctuations in jump counts bear some proportional relationship to numbers of fish entering, these counts can be used for comparisons with environmental records. Such correlations indicate that the intensity of river entry is not directly related to the intensity of any phenomenon

recorded so far (air and water temperatures, river discharge, rainfall, dissolved organic matter, hours of sunshine), nor to the rate of change of intensity. However, by applying ethological concepts, particularly that of "releaser" stimuli (Eibl-Eibesfeldt and Kramer, 1958; Baerends, 1957; Tinbergen, 1951), it is possible to produce a hypothesis to explain the grouped distribution of salmon entries.

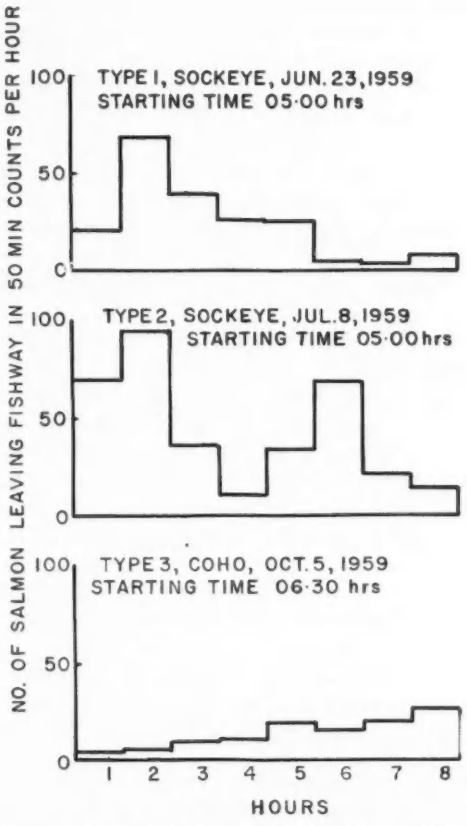
NO. OF SALMON LEAVING FISHWAY IN 50 MIN COUNTS PER HOUR
100
50
0
TYPE 1, SOCKEYE, JUN. 23, 1959
STARTING TIME 05·00 hrs
TYPE 2, SOCKEYE, JUL. 8, 1959
STARTING TIME 05·00 hrs
TYPE 3, COHO, OCT. 5, 1959
STARTING TIME 06·30 hrs
1 2 3 4 5 6 7 8
HOURS

FIG. 3. Numbers of salmon leaving the fishway at Great Central Lake dam. Notice the fluctuations from hour to hour. The daily distribution of departures tends to fall into one of three patterns: *type 1*, an early morning peak; *type 2*, two morning peaks; and *type 3*, an afternoon peak. Counts start at dawn and continue for 8 hours.

Figure 4 shows that in late summer, 1959, sudden increases of jumping, followed by 2–7 days' high counts, such as occurred on July 12–13, 24–25, 28, August 2–3 and 11–12, took place within 24 hours of changes from two or more days of relatively stable sunny weather to cloudy weather. Such weather changes

in the investigated area are largely of cyclonic origin (Trewartha, 1954) as is confirmed by synoptic weather maps for these periods. The weather changes were accompanied by very light rain or none, and consequently did not increase river discharge. However, discharge did rise on August 8 during sunny weather, through removal of stoplogs from Great Central Lake dam. No increase in jumping resulted.

These observations give somethat different results from other similar work (Hunter, 1959, for *Oncorhynchus gorbuscha* and *O. keta*; Davidson *et al.*, 1943, for *O. gorbuscha*; Huntsman, 1948, for *Salmo salar*; Hayes, 1953, for *S. salar*) which showed that river entry was related to several-fold increases in discharge. Such freshets, except those artificially produced by dam control, follow heavy rain which in turn is the result of cyclonic weather with frontal movements over the watershed area. Consequently there is a general environmental situation common to these previously investigated rivers and the Somass River. This environmental situation is "weather change arising from the approach of an atmospheric warm front". It "releases" upriver movement by salmon accumulated offshore. The subsequent grouped entry shows a 24-hour rhythm and takes several days to complete.

There appear to be at least two effective stimuli producing this response. In some cases, particularly in rivers and creeks during rainy seasons, the stimulus is related in some way to massive increases of discharge following rain, but it may be something else under other conditions. The Somass River summer observations strongly suggest that sockeye entry can be initiated through the visual cue of cloud formation in a previously clear sky.

Figure 4 illustrates a period when the relationship between river entry and weather changes was easily seen. There are however periods, during the early runs of sockeye in June, of unstable weather with frequent rain, clouds and only intermittent sunny days, when series of rapid weather changes have less consistent effects on river entry. Futhermore, in 1961, a hot and dry summer, July and August sockeye migration was light. Finally, in the last week of August an unusually late sockeye run entered in spite of continuing sunny weather. It appears, then, that the relationship between weather and sockeye migration is most pronounced in July and August. Early and late runs (that is, June and late August) are liable, not to show the relationship.

DISCUSSION

Some general conclusions can be drawn from the results obtained to date.

It now appears that, as with many other animals, the migrations of adult salmon are complex forms of movement. It is not a simple matter of fish swimming against a current and trying to pass obstructions as they come to them. There are patterns to salmon movements, in that they pass through different habitats in characteristically different ways. They migrate through only a fraction of the total water space available to them, and spend only a fraction of the available time actually migrating. The remainder of the time is

spent performing a number of non-progressive activities. The biological function of some of these is quite obscure at present. Salmon spawning migrations can profitably be regarded as a series of alternating progressive and non-progressive stages, each of which, as well as the changes from one to another, are susceptible to investigation by systematic observation and standard behavioural analytical methods.

These conclusions lead directly towards some potential management applications.

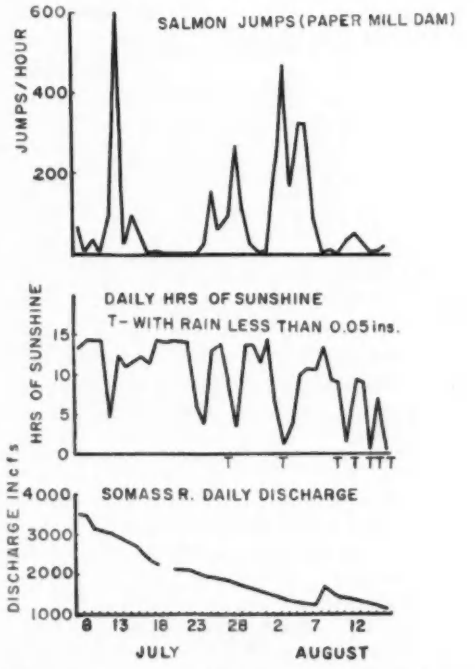

FIG. 4. Summer entry of sockeye salmon into the Somass River during 1959, as indicated by daily changes in standardized counts of jumping at Paper Mill Dam, the head of tidal water. Salmon entry occurs in groups lasting several days, each of which starts within 24 hours of extensive cloud formation after two or more days of virtually clear skies as shown by daily hours of sunshine. No correlation between salmon entry and changes in river discharge is indicated.

First, these preliminary studies have shown that it is possible to observe and record salmon movements systematically, and to reveal both spatial and temporal patterns of behaviour. It is, therefore, practical to undertake studies of this type in areas where proposed water-use developments, such as dams and pollution, threaten to interfere with salmon runs. Such studies form a basis

for logical predictions of the effects of proposed industrial developments. They should, of course, be supplemented by comparable studies after the development is complete and in operation.

A second potential application concerns the design of fish diversion facilities. These should take into consideration existing migration patterns in the area where the diversion is to be constructed, and possible pattern changes due to construction. Fishway entrances should be located where salmon are strongly orienting, and should be designed to supersede existing guiding stimuli. Salmon should enter a fishway with as little as, or less, hesitation than they had shown in passing through the area before the fishway existed.

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Radioactive Caesium as a Fish and Lamprey Mark[1]

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ABSTRACT

Experiments to test radioactive caesium-137 as a fish and lamprey ammocoete mark are described. The biological half-life (turnover) of caesium in speckled trout (*Salvelinus fontinalis*) was 47.20 days. A successful field trial was carried out, using Cs-137 for marking ammocoetes for subsequent recapture in streams undergoing chemical treatment for lamprey control.

INTRODUCTION

In a previous paper (Scott, 1961), it was shown that the use of radioactive iron as a fish mark is necessarily limited to fish over 8 cm long; the insolubility of iron compounds necessitates their direct injection into the specimens. In many population studies, this limitation may not be serious; however, where smaller specimens must be marked, some other radioisotope must be found which can be absorbed directly from the water.

Caesium-137 is one of the cheapest and most easily obtainable radioisotopes, primarily because it is a fission product, rather than a "manufactured" isotope such as iron-59. Most inorganic caesium compounds are highly soluble in water, and moreover, this element is quite similar chemically to potassium, a normal vertebrate body constituent. For these reasons, Cs-137 was selected to be tested as a marker for small fish and larvae of lampreys. Although other marking methods such as fin clipping, tattooing, etc., do exist for small fish, there has been no successful marking of ammocoetes to date. A method of marking these animals has therefore much practical value in connection with the sea lamprey control program being carried out on the Great Lakes.

The present experiment was divided into three parts: (1) determination of biological half-life of caesium in speckled trout, *Salvelinus fontinalis*; (2) absorption and retention of Cs-137 from aqueous solutions by larvae of American brook lamprey, *Entosphenus lamottei*, and sea lamprey, *Petromyzon marinus*; and (3) field trials of the marking technique, marking ammocoetes for subsequent recapture in streams.

MATERIALS AND METHODS

Ten millicuries of Cs-137 were obtained for the experiments. The material was in nitrate form, in 0.1 normal nitric acid, and was carrier-free, i.e., there was no stable caesium present. On receipt, the solution was diluted to make a

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stock of 40 microcuries (μc) per ml, to which was added 5 ppm of acriflavine hydrochloride as an antibiotic.

Two methods of introduction of the radioisotope into the specimens were used. For the turnover study, the material was injected directly into the body cavity, as described previously (Scott, 1961). For the other experiments, solutions of 0.01–0.03 μc/ml in tap water were made, the ammocoetes were introduced into the solutions, left for preset times and then removed to running fresh water.

Radioassays were carried out in two ways. The trout were assayed in the constant geometry tank described previously (Scott, 1961). Data from the ratemeter were recorded continuously on a strip chart, from which numerical data were derived. These readings were then analyzed by fitting the least squares line according to the regression:

$$\log N_t = \log N_0 - bt \qquad \ldots (1)$$

where N_0 and N_t are the background-corrected count rates at times zero and t, respectively. The effective half-life (T_e) of the element was then calculated from the slope b, using the relationship:

$$T_e = \frac{\log 2}{b} = \frac{0.3010}{b} \qquad \ldots (2)$$

whence the biological half-life (T_B) may be calculated from the expression

$$\frac{1}{T_e} = \frac{1}{T_B} + \frac{1}{T_P} \qquad \ldots (3)$$

where T_P is the known physical half-life.

Radioassay of the ammocoetes was made individually by insertion of the animal into the well of a scintillation counter. The counter was connected to a 200-channel pulse height analyzer, and a particular specimen was judged marked or unmarked depending on whether a discernible Cs-137 spectrum appeared on the display in 1 minute, after background correction. This method is only semi-quantitative, but proved to be completely satisfactory in the present experiments.

The specimens used came from three sources. The trout belonged to a stock of hatchery trout maintained in our laboratory for general purposes. Ammocoetes for the absorption and retention study were captured in Venison Creek, a tributary of Big Creek, which flows into Long Point Bay of Lake Erie. The method of capture was by electric shocker. The larvae used in the field trials were taken from two small streams tributary to Havilland Bay, Lake Superior, and one small stream on St. Joseph's Island in Lake Huron near Sault Ste. Marie. Of the latter group, approximately one-third (800) ammocoetes were captured by treating the streams with the lampricide TFM (3-trifluormethyl-4-nitrophenol), the remainder by electric shocker. Recaptures of ammocoetes in the field trials were made by collecting dead animals after treatment of the streams with TFM. The larvae were packaged, frozen and returned to the laboratory for radioassay. Some cross-contamination from specimen to specimen was found because the animals were not packaged individually; however, the contamination was minor in comparison to the count rate of the marked animals and did not interfere with the results.

RESULTS

GROUP I

Ten *Salvelinus fontinalis*, about 12 cm long, were injected with 0.25 ml (10 μc) of stock solution on December 2, 1960. The fish were placed in the constant-geometry tank, and continuous readings of the radiation level were made on the strip-chart recorder, until December 20. The data were taken from the chart, corrected for background level, and a least-squares analysis of the regression made. Table I presents the pertinent statistics. The analysis yielded an effective half-life of 47.20 days, which, with the known physical half life of 27.0 years (Anonymous, 1960), results in a biological half-life of 47.43 days. There is a negligible difference between biological and effective half-lives,

TABLE I. Analysis of radioassay data for trout marked with Cs-137.

Statistic	Symbol	Value
Number of individual radioassays	n	364
Average time of assay, days	$\bar{t}$	8.957
Average of logarithms of counts/minute	$\overline{\log N_t}$	3.049
Regression coefficient (slope)	b	−0.006378
Standard error of b	...	0.000370
Correlation coefficient	r	−0.920
Probability of significance	P	<0.01
Y-axis intercept	$\log N_0$	3.106
Effective half-life, days	T_e	47.20
Physical half-life, days	T_P	9855
Biological half-life, days	T_B	47.43
95% confidence limits of T_B, days	...	42.54 & 53.58

due to the very long physical half-live. The 95% confidence limits on the biological half-life are 42.54 and 53.58 days.

The massive dose of Cs-137 had no apparent effect on the trout; this is in direct contrast to the effort of 10 μc of Fe-59 where the latter apparently killed the specimens in approximately 30 days. All the specimens were sacrificed after 60 days to determine where the Cs-137 was situated. There appeared to be little variation in concentration throughout the soft tissues, as indicated by survey with a needle scintillation probe (Nuclear-Chicago Corp., Model DS-8-1, 2mm probe).

GROUP II

On December 22, 1960, 20 *Entosphenus lamottei* larvae, from 3.5 to 12.0 cm long, were placed in 1 litre of Cs-137 solution; the concentration was 0.01 μc/ml. The larvae were left in the solution for 24 hours at 45°F, then transferred to running water in a small tub partially filled with sand. The larvae were observed to burrow into the sand immediately. The animals were shocked out of the sand

at subsequent intervals 4 weeks apart, until April 14, 1961. They were assayed, then returned to the tub. Four larvae were killed in the first radioassay, and one more died on March 17. In addition, 25 *Petromyzon marinus* larvae were treated in the same solution on March 17 and released into the tub. These were radioassayed once on April 14. Only one *E. lamottei* and no *P. marinus* survived from April 14 to August 15 due to starvation. Table II shows the results of the radioassays. In only one case did an animal fail to maintain a mark during the assay period.

Group III

A moderate field trial of the marking technique was carried out on three streams on St. Joseph's Island in Lake Huron: Two Tree River, Gawas Creek and Richardson's Creek (Fig. 1). A total of 2410 larvae of *Entosphenus lamottei* were collected and taken to Sault Ste. Marie. A series of plastic containers, holding 6 litres of 0.03 μc/ml Cs-137 solution each, were set up on April 20, 1961.

Table II. Detectability of Cs-137 marks in ammocoetes.

Radioassay date	Time after treatment	Number marked/total
	weeks	
Entosphenus lamottei		
Dec. 22, 1960	0	20/20
Jan. 20, 1961	4	20/20
Feb. 17, 1961	8	16/16
Mar. 17, 1961	12	15/16[a]
Apr. 14, 1961	16	15/15
Aug. 15, 1961	33	1/1[b]
Petromyzon marinus		
Mar. 17, 1961	0	25/25
Apr. 14, 1961	4	25/25

[a]One specimen nearly dead — no discernible mark.
[b]Only one specimen still alive — highly discernible mark.

The larvae were divided into groups of 50, 60 and 75 and placed in the containers for 36 hours. The water temperature was 38°F (3.3°C) for the first 22 hours, but spot radioassays showed little uptake of the radioisotope by the larvae. For the remaining 14 hours, the temperature was raised to 46°F (7.8°C) and good uptake was noted. At the end of the treatment, larger groups were formed and placed in fresh water in milk cans. These were immediately taken to St. Joseph's Island and released in the three streams. Larval condition upon release was fair to good. Figures 2–4 show the points of release in each stream together with the numbers of larvae at each spot.

The Two Tree River was treated for lamprey control with TFM on May 7–10, 1961. Ammocoete collections were made wherever possible throughout

the stream system. Collecting conditions were, however, extremely bad, since heavy rains prior to treatment had caused high turbidity. The dead larvae were nearly invisible. Little information can be derived from the collections.

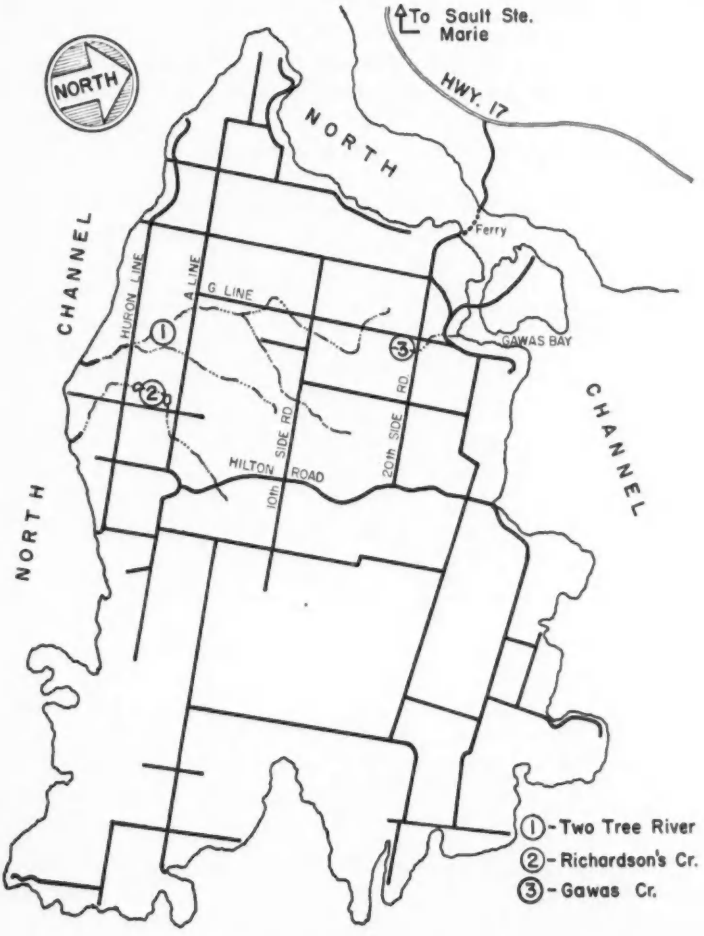

FIG. 1. St. Joseph's Island, Lake Huron, Algoma District, Ontario.

Gawas Creek was treated on April 30, 1961. Despite clear water, and despite previous successful collections made by shocker, only 5 animals were collected for 10 man-hours of observation in the stream.

In contrast to the situation on the two previous streams, conditions on Richardson's Creek during the treatment (May 4–6, 1961) could not have been

better, and substantial samples were collected. Table III presents the results of the radioassays of specimens from the three streams; Fig. 2–4 show the collecting areas.

Of 1,910 larvae planted in Two Tree River, only 24 were recaptured; in Gawas Creek, only 2 of 110 larvae were recaptured; and, in contrast, 63 out of 400 were recaptured in Richardson's Creek. There is little likelihood that these differences were caused by higher mortality rate in the two first-named streams, since all animals were treated alike and planted at about the same time.

TABLE III. Results of radioassays of ammocoetes collected during stream treatments.

Stream	Collection area	Initial number planted Apr. 21, 1961	Numbers captured during treatments		
			Marked	Unmarked	Total
Two Tree River	4 to mouth	700	9	120	129
	4c to 4a	110	0	209	209
	8 to 4	300	3	20	23
	11 to 8	300	5	25	30
	12 to 11a	100	7	103	110
	above 11	400	0	0	0
	Total	1910	24	477	501
Gawas Creek	2 to mouth	110	2	3	5
Richardson's Creek	Above dam	100	7	0	7
	5 to dam	0	0	323	323
	5 to mouth	300	56	943	999
	Total	400	63	1266	1329

DISCUSSION

The main aim of this study was the development of a method of marking ammocoetes which could be used for population estimates of streams. In spite of the very large program of research and control of sea lampreys going on at present, knowledge of the numbers of animals at present in the streams and estuarine areas is totally lacking. Thus there is a need for some method of marking. Larval lampreys have no fins which may be clipped and are generally too small for any method of tagging.

The present method of marking the animals is successful. If collecting conditions on the Two Tree River had been better, much higher numbers of marked animals would probably have been recovered. Of much more interest, however, are the results of the Richardson's Creek trial. Here, under ideal collecting conditions, a pattern emerges which suggests that the technique may be useful in defining the upper limits to which lampreys ascend streams. There is a mill pond dam on the stream (Fig. 4). Electric shocker surveys had not

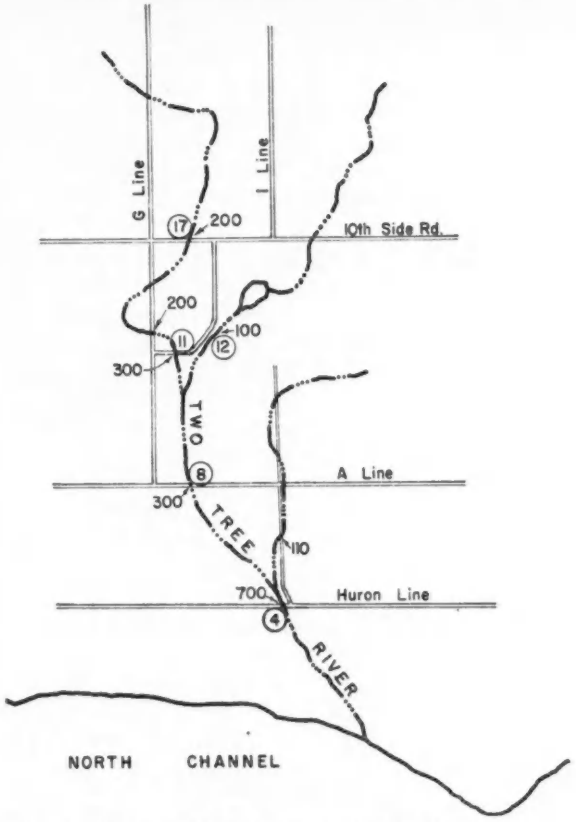

FIG. 2. Two Tree River, St. Joseph's Island, Algoma District.

discovered any larvae above the dam, but these surveys cannot be regarded as conclusive negative evidence for the presence of ammocoetes. It will be noted that 100 marked larvae were planted at the head of the pond, and subsequently 7 larvae were recovered during the treatment. All 7 were marked animals, leading to the conclusion that there was no natural population above the dam.

In contrast, no marked animals were planted between the dam and Station 5 on the Huron line. Here 323 larvae were collected, and none were marked. This result indicates that there was little or no migration from either the mill pond downstream into this area or from the lower region upstream.

Finally, 999 larvae were collected between Station 5 and the mouth of the river, of which 56 were marked. By simple proportion, this result leads to a population estimate for the lower section of 5,052 larvae of the size range recovered. The 95% confidence limits for this value are 3,722 and 9,150. No reasonable population limits can be derived from the smali samples taken from the Two Tree River and Gawas Creek.

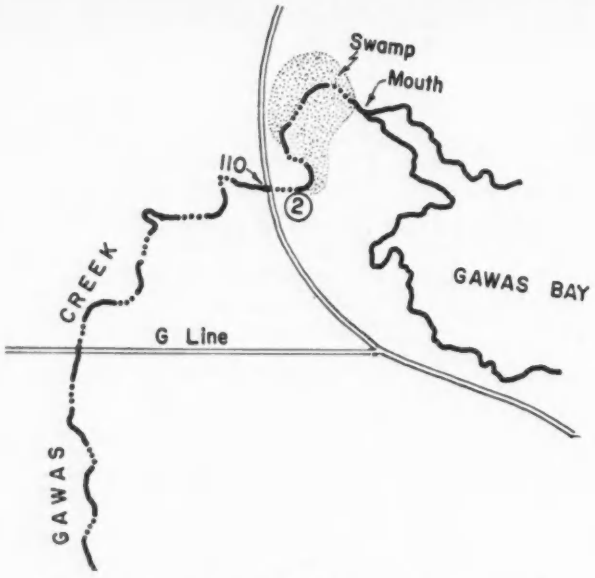

FIG. 3. Gawas Creek, St. Joseph's Island, Algoma District.

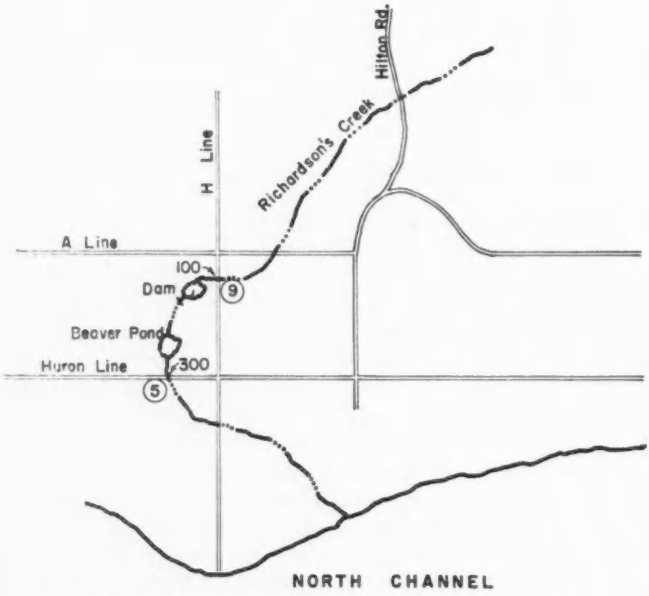

FIG. 4. Richardson's Creek, St. Joseph's Island, Algoma District.

Use of Cs-137 as a mark for ammocoetes is quite feasible. There is no indication that heavy mortalities occurred in the marked animals. Where large numbers of ammocoetes were collected in good collecting conditions, a good proportion of the marked animals were recaptured. Where conditions were bad, as in the Two Tree River, or where very few larvae were collected, as in Gawas Creek, a low number of recaptures occurred. In other words, if accurate population estimates are to be made, collecting conditions must be good and large samples obtained.

The results of the trout marking indicate that Cs-137 can also be used as a short-term mark for fish. The 47-day effective half-life of caesium is similar to that for iron-59 (Scott, 1961), although it is the short *physical* half-life of the latter which places a limitation on the length of time which a mark will remain useful. There is also the apparent result that Cs-137 is less damaging than Fe-59, probably because the latter concentrates in the blood rather than being generally distributed throughout the body. Caesium-137 emits a single 0.663 Mev β-ray with a 0.667 Mev γ-ray emitted from the daughter Ba-137m shortly afterwards. The total energy emitted lies below that of Fe-59 and therefore is less likely to cause damage.

Finally, use of Cs-137 for marking ammocoetes presents very little danger to man. Ammocoetes are not used as human food, and there is little likelihood of a predator accumulating enough Cs-137 by eating ammocoetes to present any hazard through its consumption by a person. However, the use of Cs-137 as a fish mark might present more difficulty in that, unlike Fe-59 in the blood, it would not be washed out during cleaning. Use of Cs-137 should be confined to species not usually used by man, or such fish should be marked and studied where no fishing is done.

ACKNOWLEDGMENTS

I wish to thank all the members of the Chemical Control Group, Fisheries Research Board, for their fine cooperation in carrying out the field trial. Thanks are also due to Mrs H. E. Le Maire and Mr J. Hoy for valuable assistance in the radioassay work; Mr Hoy is entirely responsible for technical assistance to the project.

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A Method of Estimating Mortality Rates from Change in Composition[1]

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ABSTRACT

This paper examines the problem of estimating mortality rates from knowledge of catch and of the change in composition caused by selective fishing on one of two classes of a closed population.

Estimators of fishing mortality in the presence and in the absence of natural mortality are given. An estimator of natural mortality is shown for the special case where final population size is known.

A numerical example illustrates the method. Certain problems are discussed and two types of application are suggested.

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INTRODUCTION

Changes in the composition of a fish population may provide estimates of important parameters. For instance, Widrig and Taft (1957) used changes in calculated length-at-age to find the fraction of a sardine (*Sardinops caerulea*) population present in one area at time 2 that came from another area since time 1. Murphy (1952) used a similar principle to estimate survival of silver salmon (*Oncorhynchus kisutch*) from the Eel River, California, during their third (final) year of life at sea. Here, factors causing early maturity selectively "remove" the males at age 2 and hence change the age and sex composition of the brood; escapement counts by age and sex provide the estimate.

Chapman (1955) derived the maximum likelihood estimators of initial population size when a harvest is selective for one class of a closed population which suffers no natural mortality during the catch interval. Classification can be for any observable character; examples are size, age, sex and color. Ricker (1958) describes the work of Chapman (1955) and Murphy (1952).

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The present paper examines the problem of estimating mortality rates from knowledge of catch and of the change in composition caused by selective removal of one class during the catch interval. From a mathematical viewpoint it simply shows how Chapman's (1955) fundamental work relates to the theory of fishing as developed by authors like Ricker (1958) and Beverton and Holt (1957).

The parallel to the theory of fishing was discovered incidentally in a search for ways to estimate mortality in a population of Pacific salmon (*Oncorhynchus*) exploited both by an offshore and inshore fishery. It soon was apparent that inexact knowledge of availability to offshore fishing rendered the method inappropriate for that problem. Nevertheless, the method itself is of interest for two reasons. First, catch is the one item of information accessible to relatively complete study. Second, Chapman (1955) indicated that extension of his basic theory to include open populations and natural mortality may not be too difficult.

Our objective is therefore to stimulate wider interest in the theory and practice of change-in-composition methods, with particular reference to estimation of mortality rates. First, we give a way to estimate fishing mortality when natural mortality is absent during the catch interval. Next, natural mortality is allowed and its effect on estimation of fishing rates examined. An estimator of natural mortality is then given for the special case of a known final population and of equal natural mortality rates on each of the two classes into which total population is divided. Finally, we discuss certain implications of the method and suggest possible applications.

For their competent reviews and helpful suggestions I am indebted to Dr W. E. Ricker of the Fisheries Research Board of Canada Biological Station, Nanaimo, B.C.; to Dr G. V. Paulik of the Department of Mathematics, University of Washington, Seattle, Washington; and to Messrs R. A. Fredin and D. D. Worlund, biometricians at the Seattle Biological Laboratory of the United States Bureau of Commercial Fisheries.

ESTIMATION OF FISHING MORTALITY WITH NATURAL MORTALITY ABSENT

Let a population be divided into two classes — such as small and large, or male and female — and designate these classes by X and Y. If classification is by length, for instance, gill nets of a particular mesh size will remove a higher fraction of those initially present in the X class (say) than in the Y class. Or anglers may take more sport fish from the X class because of a size limit. Now let:

N_{ij} = population present at time i in class j

1, 2 = subscripts designating start and end of the catch interval ($i=1, 2$)

x,y,z = subscripts respectively designating the X class, the Y class and the total population ($j=x,y,z$)

p_i = true fraction of total population in the X class at time i ($p_i=N_{ix}/N_{iz}$)

C_j = catch from class j in the catch interval ($i=1$ to $i=2$)

Assume that: (1) the p_i can be estimated from representative samples taken just before the start and just after the end of fishing, (2) fishing is selective for the X class, (3) the catches by class, C_j, are known, and (4) the population is closed.

Chapman (1955) shows that the change in p_i caused by selective removal leads to the following maximum likelihood estimators of initial population (at $i=1$, the start of fishing):

$$\hat{N}_{1x} = \frac{C_x - p_2 C_z}{p_1 - p_2} \quad \ldots (1)$$

$$\hat{N}_{1z} = \frac{p_1(C_x - p_2 C_z)}{p_1 - p_2} \quad \ldots (2)$$

Of course, the initial Y population is then found by difference.

From the standard equations of fishing theory as given in Beverton and Holt's (1957) notation, the average size of the X population in the absence of natural mortality is:

$$\bar{N}_x = \frac{N_{1x}(1 - e^{-F_x})}{F_x} \quad \ldots (3)$$

From Equation 3 (and recalling that catch is the product of fishing rate and average population, i.e., $C_x = F_x \bar{N}_x$):

$$N_{1x} = \frac{C_x}{(1 - e^{-F_x})} \quad \ldots (4)$$

Equating N_{1x} in Equation 4 with its estimate in Equation 2:

$$1 - e^{-\hat{F}_x} = \frac{C_x(p_1 - p_2)}{p_1(C_x - p_2 C_z)} \quad \ldots (5)$$

The complement of the left-hand side of Equation 5 can be found in any table of the descending exponential to give the estimated fishing rate, $\hat{F}_x$.

Estimation follows readily for F_y and F_z. Note that:

$$p_2 = \frac{N_{2x}}{N_{2x}} = \frac{N_{1x}\, e^{-F_x}}{N_{1x}\, e^{-F_z}} = p_1 \left(\frac{e^{F_z}}{e^{F_x}}\right) \quad \ldots (6)$$

From Equation 6 an estimate of F_z is given by:

$$\hat{F}_z = F_x + \ln\left(\frac{p_2}{p_1}\right) \quad \ldots (7)$$

Also, parallel to Equation 6:

$$(1 - p_2) = \frac{N_{2y}}{N_{2z}} = \frac{N_{1y}\, e^{-F_y}}{N_{1z}\, e^{-F_z}} = (1 - p_1)\left(\frac{e^{F_z}}{e^{F_y}}\right) \quad \ldots (8)$$

Proceeding as for $\hat{F}_z$ as in Equation 7, then, Equation 8 becomes:

$$\hat{F}_y = F_z + \ln\left(\frac{1 - p_1}{1 - p_2}\right) \quad \ldots (9)$$

Equations 5, 7 and 9 can therefore be used to get fishing rates for the X, Y and total populations, respectively, from observed catch data and from the change in composition as measured by representative samples of the p_i when mortality is absent.

ESTIMATION OF FISHING MORTALITY WITH NATURAL MORTALITY PRESENT

For a given set of fishing rates and initial populations the catch will be lower, of course, when natural mortality is present. The change-in-composition method is based on catches which reflect the effects of any natural mortality; hence it is worthwhile to examine the effects of this mortality on the above estimates of fishing rates.

In the first case, suppose natural mortality to operate at the same rate, M, on both the X and Y populations. Designating by the prime symbol (′) the final populations N'_{2x} and N'_{2y} which are now less than the final populations N_{2x} and N_{2y} that occurred when M was zero, note that:

$$p'_2 = \frac{N'_{2x}}{N'_{2T}} = \frac{N_{1x}\, e^{-(F_x+M)}}{N_{1x}\, e^{-(F_x+M)}} = p_1 \left(\frac{e^{F_x}}{e^{F_x}} \right) \qquad \ldots (10)$$

Equation 10 is identical to Equation 6; thus the final fraction of total population in the X class is independent of natural mortality, provided $M_x = M_y$. Recall also that p_1, measured before the start of fishing, cannot be affected by natural deaths in the following catch interval.

The question is how Equations 5, 7 and 9 are affected by non-zero natural mortality when $M_x = M_y$. If Equation 5, for instance, remains unbiased, one can write:

$$\frac{C_x(p_1 - p_2)}{p_1(C_x - p_2 C_z)} = \frac{C'_x(p_1 - p_2)}{p_1(C'_x - p_2 C'_z)},$$

where the primes designate the new catches made with natural mortality present. Recalling that the p_t are independent of natural mortality, the expression just above can be written for present purposes as a conditional identity by: (1) multiplying it by $p_1/(p_1 - p_2)$, (2) inverting and subtracting unity from both sides, (3) multiplying by −1 and cancelling p_2, and (4) inverting back again. This results in:

$$\frac{C_x}{C_z} \stackrel{?}{=} \frac{C'_x}{C'_z} \qquad \ldots (11)$$

We found that Equation 11 is not a general identity, but discovered by numerical models that these catch ratios are equal for practical purposes (to two-place accuracy). One such model is shown in Table I. The second column of Table I uses symbols given previously and includes certain definitions for readers unfamiliar with the theory of fishing.

A value of $p_t = 0.7$ was assigned to the initial total population of 10,000 fish to give initial numbers of 7000 and 3000 in the X and Y populations, respectively. To the latter were assigned fishing rates of $F_x = 0.6$ and $F_y = 0.2$ as M varied from 0 to 0.5. The value of $F_z = 0.46$ was found from Equation 7 after p_2 was computed, and checked by dividing the average total population by its catch. Otherwise, the calculations of Table I are self-explanatory.

The slight downward bias (−2 for total population, −1 for the X and Y populations) in initial population estimates made for $M = 0$ from Equations 1 and 2 is due only to rounding in the course of calculation. The feature of interest is that the estimates of fishing rates—the $\hat{F}_z$, $\hat{F}_x$ and $\hat{F}_y$—are independent of M and

equal to the true rates despite the increasing bias in initial population estimates as M approaches 0.5.

The next case occurs when natural mortality operates at different rates on the X and Y population ($M_x \neq M_y$). Here, it is intuitively reasonable to expect bias in using Equations 5, 7 and 9; we wish to get a notion of its magnitude.

Figure 1 shows the bias in using Equation 5 when M_x and M_y each vary in increments of 0.1 from 0 to 0.5. The calculations were carried out with the same N_{ij}, F_j and p_i as in Table I.

The bias shown in figure 1 is for practical purposes a linear function of the difference between fishing rates in the X and Y populations (rather than of their absolute magnitude). For a given difference this bias is lower when natural mortality in the dominant X population exceeds that in the smaller Y population.

ESTIMATION OF NATURAL MORTALITY WITH FINAL POPULATION KNOWN

In special circumstances, as in certain runs of anadromous species, the final population may be known. One can then estimate natural mortality in the first case above ($M_x = M_y$).

Once the fishing rates are estimated without bias, division of known catch by estimated fishing rate gives an unbiased estimate of average population:

$$\hat{\bar{N}}_j = \frac{C_j}{\hat{F}_j} \qquad \ldots (12)$$

The general expression for average size of the j^{th} population is:

$$\bar{N}_j = \frac{N_{1j}\left[1 - e^{-(F_j+M)}\right]}{F_j+M}$$

On solving for initial population, this becomes:

$$N_{1j} = \frac{C_j + M\bar{N}_j}{1 - e^{-(F_j+M)}} \qquad \ldots (13)$$

Initial population can also be put in terms of the known final population:

$$N_{2j} = N_{1j}\, e^{-(F_j+M)}$$

whence

$$N_{1j} = \frac{N_{2j}}{e^{-(F_j+M)}} \qquad \ldots (14)$$

The right-hand sides of Equations 13 and 14 can be equated; expanding and simplifying the resulting expression gives:

$$N_{2j}\, e^{M} - \bar{N}_j e^{-F_j} M = e^{-F_j}(C_j + N_{2j}) \qquad \ldots (15)$$

With N_{2j}, F_j and C_j known, trial values for M can be inserted in the left-hand side of Equation 15 until the known quantity on the right-hand side is closely approximated. Referring to Table 1, for instance, suppose that $N_{2z} = 4666$ were known and one wished to estimate M from Equation 15. Inserting numerical values from the sixth column of Table 1:

$$4666\, e^{M} - \bar{N}_z\, e^{-0.46} M = e^{-0.46}(3241 + 4666)$$

TABLE I. Numerical model to illustrate computation of fishing rates by the change-in-composition method described in the text.

Quantity	Symbol		Numerical values					
1. Initial total population	N_{1x}		10000	10000	10000	10000	10000	10000
2. Fraction of total population in X class	p_1		0.7	0.7	0.7	0.7	0.7	0.7
3. Initial X population	p_1N_{1x}		7000	7000	7000	7000	7000	7000
4. Initial Y population	$(1-p_1)N_{1x}$		3000	3000	3000	3000	7000	3000
5. Instantaneous rate of natural mortality	M		0	0.1	0.2	0.3	0.4	0.5
6. Instantaneous fishing rate on X population	F_x		0.6	0.6	0.6	0.6	0.6	0.6
7. Instantaneous fishing rate on Y population	F_y		0.2	0.2	0.2	0.2	0.2	0.2
8. Instantaneous fishing rate on total population	F_z		0.46[a]	0.46[a]	0.46[a]	0.46[a]	0.46[a]	0.46[a]
9. Catch of j-type fish $(j=x,y)$[b]	C_j	$(j=x)$ $(j=y)$	3158 544	3020 518	2891 495	2769 472	2655 451	2547 431
10. Total catch	C_x+C_y		3702	3538	3386	3241	3106	2978
11. Natural deaths of j-type fish[c]	D_j	$(j=x)$ $(j=y)$	0 0	503 259	964 495	1385 708	1770 902	2123 1079
12. Total natural deaths	D_x+D_y		0	762	1459	2093	2672	3202
13. Final X population	$N_{2x}=N_{1x}-C_x-D_x$		3842	3477	3145	2846	2575	2330
14. Final Y population	$N_{2y}=N_{1y}-C_y-D_y$		2456	2223	2010	1820	1647	1490
15. Final total population	$N_{2x}+N_{2y}$		6298	5710	5155	4666	4222	3820
16. Fraction of final total population in X class	$p_2=\frac{N_{2x}}{N_{2x}+N_{2y}}$		0.61	0.61	0.61	0.61	0.61	0.61

TABLE I. (continued)

Quantity	Symbol	Numerical values					
17. Estimate of initial total population	$(C_x - p_2C_2)/(p_1 - p_2)$	9998	9576	9173	8800	8448	8116
18. Estimate of initial X population	$p_1(C_x - p_2C_2)/(p_1 - p_2)$	6999	6703	6421	6160	5914	5681
19. Estimate of initial Y population	Item 17 minus item 18	2999	2873	2752	2640	2534	3435
20. Estimate of seasonal fishing mortality rate for X population	$(1-e^{-\hat{F}_x}) = \frac{C_x(p_1 - p_2)}{p_1(C_x - p_2C_2)}$	0.45	0.45	0.45	0.45	0.45	0.45
21. Estimate of instantenous fishing rate for X population	$\hat{F}_x$	0.6	0.6	0.6	0.6	0.6	0.6
22. Estimate of instantaneous fishing rate for total population	$\hat{F}_z = \hat{F}_x + \ln\left(\frac{p_2}{p_1}\right)$	0.46	0.46	0.46	0.46	0.46	0.46
23. Estimate of instantaneous fishing rate for Y population	$\hat{F}_y = \hat{F}_z + \ln\left(\frac{1-p_1}{1-p_2}\right)$	0.2	0.2	0.2	0.2	0.2	0.2

[a] An average value for any one "experiment". F_x and F_y are fixed; yet F_z decreases from 0.480 at the start to 0.444 after the last removal (which reduces p_2 to 0.61), since the more vulnerable X population declines faster than the Y population.

[b] $C_j = \frac{F_j N_{1j}\left[1 - e^{-(F_j + M)}\right]}{F_j + M}$

[c] $D_j = \frac{MN_{ij}\left[1 - e^{-(F_j + M)}\right]}{F_j + M}$

Of course (recalling Equation 12):

$$\hat{\bar{N}}_z = \hat{\bar{N}}_x + \hat{\bar{N}}_y = \frac{C_x}{\hat{F}_x} + \frac{C_y}{\hat{F}_y} = \frac{2769}{0.6} + \frac{472}{0.2} = 6975$$

On substitution of 6975 for $\hat{N}_z$:

$$4666\, e^M - (6975)\,(0.63)M = (7907)\,(0.63),$$

$$4666\, e^M - 4394M = 4981$$

A trial value of $M = 0.2$ leads to:

$$(4661)\,(1.22) - (4394)\,(0.2) = 4814$$

Since $4814 < 4981$, try a larger M (say $M = 0.3$). This gives:

$$(4666)\,(1.35) - (4394\,(0.3) = 4981$$

Thus $M = 0.3$ is the correct value, as verified from Table I.

DISCUSSION

Among the requirements for practical application of the method just described is that fishing be intensive and selective enough to make p_2 significantly less than p_1. Of course, when X and Y are *size* classes and individuals are actively growing in the catch interval, the effects of growth require evaluation. Also, one must face the problem of obtaining representative samples at times 1 and 2 to estimate the p_i. For gill net fisheries, at least, recent contributions by Holt (1957), Olson (1959) and McCombie and Fry (1960) to the theory of gill net selection strongly indicate that one can achieve truly representative sampling of the available population.

A more serious problem might occur when p_2 is observed to be significantly less than p_1 (hence indicating feasibility of the method), but where the $\hat{p}_i$ are not measured on the *same* total population, no matter how accurately they measure the p_i on the total populations available at time i. If size is the criterion, for instance, p_2 might be lower than p_1 both from selective fishing on the X population *and* from an influx of small or departure of large fish during the catch interval. In this case estimation of fishing rates by Equations 5, 7 and 9 is not valid. Were estimates of availability made — as from the methods of Widrig (1954) or Gulland (1955) — one perhaps could set up models of initial population size and availability (in combination with fishing rates estimated for full availability) that *could* give the observed change in p_i, then attempt iterative solutions for the whole system with whatever auxiliary information was at hand. However, these complications will in general require extension of the theory to open populations as implied by Chapman (1955).

Whether it will be reasonable to assume equal rates of natural mortality on the X and Y population depends on the nature of the classification made. Of course, X and Y can be whatever arbitrary classes render this assumption most reasonable. The problem of class differences in natural mortality may not be serious in practice. In the first place, natural mortality usually is low for a

single fishing season. Secondly, Fig. 1 shows the bias in $\hat{F}_x$ to be low (0.1) relative to the high (for a single fishing season) difference of 0.3 between M_x and M_y.

One obvious application might be to a closed population of tagged fish subsequently captured by a gear selective for size or some other character. In this case, the p_i and C_j presumably would be known with high precision relative to other applications. The usual assumption in tagging theory would apply in making inferences about untagged fish.

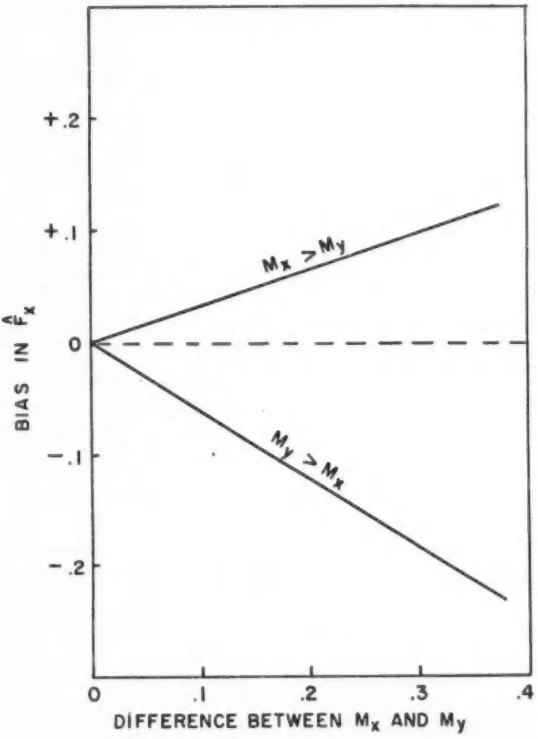

FIG. 1. Bias in estimate of fishing rate for X population when $F_x = 0.6$ and $F_y = 0.2$.

The case of a known final population is admittedly unique. Yet we do find size-selective fisheries on anadromous species whose growth is negligible in the catch interval and whose spawners are counted or estimated. In the Pacific salmons (*Oncorhynchus* spp.), for instance, p_2 as measured on the spawning grounds may be less than p_1 as measured in the river or estuarine fishery; actual causes of the estimated natural mortality, as from dams, may be of particular interest in such applications. Other applications may be to inland species:

where counts of poisoned fish are made at the end of an angling season on lakes or streams, or where water is drawn down and fish stranded.

In common with other methods of estimating fishing rates, the change-in-composition method may suffer most from inexact knowledge of availability and from the difficulty of getting representative samples. Yet continuing interest in methods of assessing important parameters of fish populations, and particularly the fact that catch is accessible to thorough study, suggest that the simple principles involved may find future application.

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NOTES

Fat Hydrolysis in Frozen Fillets of Lingcod and Pacific Gray Cod

It has been known for several years that lipids in fish muscle undergo changes during storage. Dyer (1951, 1953) indicated that fat spoilage was involved in the deterioration occurring under frozen storage even in the non-fatty species of fish. The changes taking place in the muscle lipids were studied for various Atlantic species (Dyer and Morton, 1956; Dyer and Fraser, 1959; Lovern *et al.*, 1959) and it was found that the lipids were hydrolyzed with the formation of free fatty acids. Lovern *et al.* (1959) found that it was the phospholipids which were breaking down and recent work by Bligh (1961) has shown that hydrolysis of phosphatidylethanolamine and phosphatidylcholine is mainly responsible for the increase in free fatty acids. Apart from some early work by Brocklesby (1933) on salmon, there are no data available for the formation of free fatty acids in Pacific species, and an investigation was therefore commenced to study the free fatty acid formation in lingcod (*Ophiodon elongatus*) and the Pacific gray cod (*Gadus macrocephalus*), both species being caught commercially off the coast of British Columbia.

Fillets were obtained from freshly caught fish, wrapped in cellophane and stored in wax cartons at +10°F (−12°C). The lipids were extracted from the muscle tissue as described by Bligh and Dyer (1959). The troublesome cloudy upper layer mentioned by Olley and Lovern (1960) was not encountered under the conditions of storage used in the present experiment. The extracted lipids were chromatographed on silicic acid to remove phospholipids (Olley and Lovern, 1960), and the free fatty acids in ethanol solution were titrated with 0.02*N* KOH using phenolphthalein as indicator.

Table I shows the lipid composition of fresh lingcod and Pacific gray cod fillets. The total lipid and free fatty acid composition of the Pacific gray cod

TABLE I. Lipid composition of fresh lingcod and Pacific gray cod fillets. (Each value is the mean for 10 fillets ± the standard deviation.)

Species	Total lipid (% of wet muscle)	Free fatty acids (% of total lipid)
Lingcod	0.85 ± 0.09	3.4 ± 0.4
Pacific gray cod	0.58 ± 0.03	5.2 ± 0.3

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resembles closely the values for the Atlantic cod (*Gadus callarias*) (Olley and Lovern, 1960). The lingcod has a slightly higher lipid content but free fatty acid as a percentage of the total lipid is somewhat less than that in the gray cod. These two effects balance out so that the free fatty acid comprises 0.030 and 0.029% of the wet muscle in Pacific gray cod and lingcod respectively.

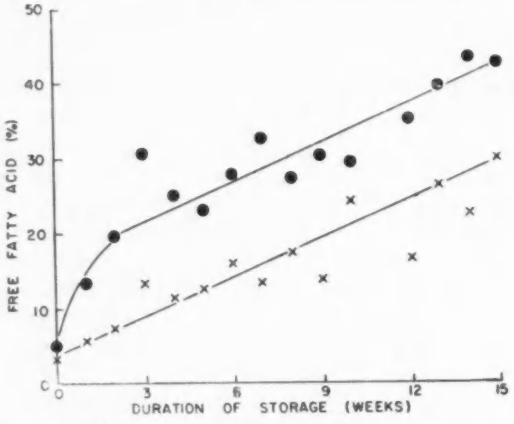

FIG. 1. The formation of free fatty acids in lingcod and Pacific gray cod fillets. •—• Pacific gray cod; ×—× lingcod. Each value is the mean value for 10 fillets.

The increase in the free fatty acid content of the fillets is shown in Fig. 1. The rates of hydrolysis differ in the two species. The Pacific gray cod lipids hydrolyze rapidly during the initial 2 or 3 weeks of storage, but thereafter a less rapid but continuous process ensues. The lingcod lipids on the other hand exhibit a more uniform rate of hydrolysis during the 15-week experimental period. The results for the Pacific gray cod resemble closely those obtained for the Atlantic cod at similar storage temperatures (Dyer and Fraser, 1959).

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